NORDISK ARKITEKTURFORSKNING
NORDIC JOURNAL OF ARCHITECTURAL RESEARCH

1

ISSUE 1 2020

NORDISK ARKITEKTURFORSKNING
Nordic Journal of Architectural Research

1–2020

Nordic Journal of Architectural Research
ISSN: 1893–5281

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NORDISK ARKITEKTURFORSKNING
NORDIC JOURNAL OF ARCHITECTURAL RESEARCH

ARCHITECTURAL REPERTOIRE AND DAYLIGHT METRICS

MALIN ALENIUS AND MARJA LUNDGREN

Abstract

In this article, we highlight the importance of architectural repertoire, methods and tools to uncover basic components set by building science in performance-based regulation. This article elucidates the potential of architecturally-grounded methods when assessing daylight metrics often used in legislation and certification schemes, by rendering the daylight factor metric intelligible through geometry. The empirical material used comprises five architectural cases from 1917 to 2016. These five cases originate from an exhibition room on daylight presented in relation to architectural composition, historical changes in Swedish building regulation, and the 2014 daylight factor building code requirement. As in many other countries, building regulations in Sweden have undergone a historical change from prescriptive regulation to performance-based regulation. With regards to regulating daylight, this has meant replacing requirements based on geometrical relationships with abstract building science metrics. Additionally, we review these findings in relation to findings from a numerical analysis of 2014 daylight factor building code requirements from a larger number of Swedish residential buildings from the twentieth century. This article argues that architectural research based in drawings and geometrical relationships and case study material, whether historical or contemporary, can guide practitioners towards a new understanding of building code.

Keywords:
daylight, performance-based regulation, architectural representation, case-study methods, architectural repertoire, building science, context-dependent knowledge, context-independent knowledge

Introduction

In the second half of the twentieth century, a transition from prescriptive building regulation to performance-based building regulation commenced in Sweden, as in many other places such as the UK, Australia and the other Nordic countries. As there is a long history of daylight regulation in most countries, the transition from geometrically-based rules to building science metrics serves as a meaningful example of the implications of this for architectural knowledge and practice. In this article, five historical cases from between 1917 and 2016 in Sweden are used to elucidate the relationship between architecture, building code, and daylight. The analysis of these five cases highlights the importance of architectural repertoire, methods and tools to uncover the basic components of daylight metrics in relation to architectural composition. Presented in depth, these five cases are also reviewed in relation to the findings of another numerical study based on a larger number of cases. The two studies stem from different knowledge traditions – one grounded in architectural history, and the other based in building science. Nevertheless, a common research question can be identified that makes a comparison between the knowledge outcome of the exhibited five cases and the numerical analysis relevant: *How does the 2014 Swedish building code requirement on daylight availability relate to the daylight availability in typical Swedish residential multi-family buildings from the twentieth century?* Both studies were carried out by comparing specific but typical examples of design and building practice. The selection of typical architectural cases for both the exhibition and the numerical analysis was carried out by the authors of this article in collaboration with architects and planners at their architectural firm at the time. In this article, we have positioned these comparisons in a historical context, as well as questioned how architectural practice should best respond to an environment in which calculation has increasingly formed the basis for decision-making processes in relation to the construction of the built environment.

The daylight performance requirement was reintroduced in 2014

Until 1960, daylight availability in Sweden was regulated through urban geometrical relationships in planning and building acts. These initially included prescriptions of actual dimensional requirements in 1874. Between 1931 and 1960, the requirements were described in terms of parametrical relationships that stated that the distances between buildings needed to be equal to or exceed the building heights (Granath, 2001); i.e., daylight was regulated on an urban scale and assessed through drawings. In the 1970s, a daylight factor metric, defined as a specific measure or calculation point, was introduced into the Swedish building code (Svensk Byggnorm, 1975, 38:1, p. 237). This metric expresses the percentage of daylight illuminance indoors on an overcast day in relation to outdoor illuminance. This daylight requirement was defined in relation to single rooms and required calculation. It did not yield an immediately intelligible result in terms of drawings, and it could not immediately be related to the overall conditions of an urban plan. In 1994, the daylight factor was omitted from Swedish building code (BBR, 1994, p. 75-76), but it was reintroduced in 2014 (BBR, 2014, 6.322, p. 105; Statsrådsberedningen, 1998, p. 25-26). As there was no verifiable requirement between 1994 and 2014, several detailed development plans that were adopted during this period were not analysed from a daylight perspective on the urban level. Swedish cities in the twenty-first century are undergoing drastic transformations because of urbanisation and a large housing shortage, and there has been market pressure to densify cities (Boverket, 2016, p. 5; Gunnartz, 2017, p. 11-28; Boverket, 2017, p. 5-8). Not understanding this metric in planning stages, especially in dense areas, causes difficulties on the building design level and can potentially lead to the denial of building permits.

Traditional architectural representation as a method of inquiry

The architectural case study was made for an exhibition called *Bo.Nu.Då* (Living Now and Then) at the Swedish Architecture and Design Museum, ArkDes, in 2016. The exhibition of the five cases was produced under the lead of the authors of this article (Alenius et al., 2016). These cases were typical and architecturally renowned multi-family residential blocks from 1920s, the 1950s and 1960s, the 1970s and the early 2000s. They relate to a canon or repertoire of distinguished Swedish multi-storey residential buildings. The ArkDes exhibition room was dedicated to the pressing need for architectural knowledge on the relation between the daylight factor metric[1] and an architectural repertoire of case studies. In our experience, architectural colleagues have repeatedly stated that this metric is intangible and difficult to understand; it is therefore not easily translated back into decision-making regarding form or design. Consequently, an aim with the exhibition room was to position the daylight factor metric in representational methods grounded in architectural knowledge. Another important aspect woven into the exhibition concerned the influence of the contemporary legislation when each case was built, in terms of urban planning, building design and the consequential daylight availability indoors. In building science, daylight is described as composed by two components: direct sunlight and diffuse skylight (Boyce, 2003, p. 28) (see Figure 1). The daylight factor metric only accounts for diffuse skylight and reflected skylight.[2] It is therefore based on the relation between the urban and building design and its relation to an unobstructed sky. As part of unfolding the basis for this metric, the exhibited cases showed geometrical representational methods to predict daylight that are now almost forgotten in Swedish architectural practice, such as the no-skyline[3] (see Figure 2) and the obstruction angle. Each case was also assessed through digital calculations and the

1 The Swedish building code addresses a daylight factor point, situated in the middle of a room, located one metre from the darkest wall and expressed as a percentage of the daylight illuminance indoors on an overcast day in relation to the outdoor illuminance from an unobstructed sky. One per cent is required for all rooms used more than occasionally.

2 In 2017, Alan Lewis showed how the more detailed versions were developed in British standards during the 20th century to include all reflections of the diffuse skylight, including those from interior surfaces.

3 No-skyline is described in Ralph Galbraith Hopkinson, Peter Petherbridge and James Longmore: *Daylighting*, (London: Heinemann, 1966), p. 579 as "A line which separates all points on the working plane at which the sky is directly visible from those at which no section of the sky is directly visible." Compare with Vitruvius around approximately 30 B.C. in Vitruvius, *The Ten Books on Architecture*, trans. by Morris Hicky Morgan, Book IV (Cambridge, Mass.: Harvard University Press, 1914), chapter VII, p. 185: "On the side from which the light should be obtained let a line be stretched from the top of the wall that seems to obstruct the light to the point at which it ought to be introduced, and if a considerable space of open sky can be seen when one looks up above that line, there will be no obstruction to the light in that situation."

resulting daylight factor was illustrated in the plan.[4] On the urban level, sunlight studies – frequently used in the planning process – were presented for each case (BBR, 2014, 6:323, p. 105; BBR, 2019, 6:323, p. 98). In addition to the graphical representations, we made a film showing the living room interior of each case. The film, developed through visualization, shows sequences of light and dark, sunlight and daylight on the 21st of June, 6 seconds per each hour day and night.[5] The visualizations in the film were based on information from drawings, photographs and on-site measurements.[6] The exhibition room aimed to give the audience a possibility to combine the readings of the representations of metrics as well as dynamics of daylight and sunlight in the interior space through the film. By also considering experiential aspects of daylight that were evident in the cases, the exhibition room presented daylight in the built environment, demonstrating the complexity that constitutes it, rather than only showing an indicator of diffuse skylight. The aim was thus to give an opportunity to relate measurable and unmeasurable aspects of daylight to each other, as well as to the traditional architectural representations of drawings in plans and sections.

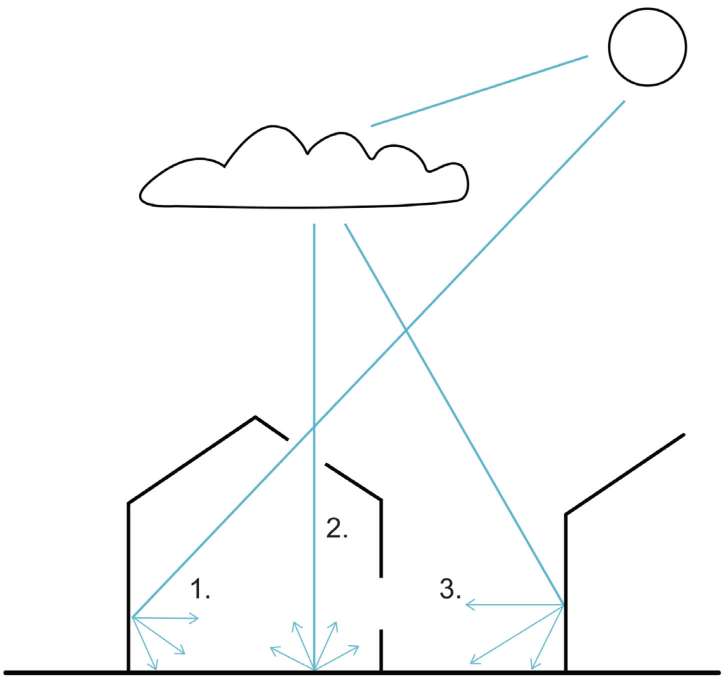


Figure 1
Daylight definition. 1. sunlight 2. skylight 3. reflected light. Illustration based on N. Lechner.
SOURCE: MALIN ALENIUS.

4 The digital calculations of the daylight factor in a point were carried out in the program Velux Daylight Visualiser, <https://www.velux.com/article/2016/daylight-visualizer>. The point is illustrated by a cross inside of a dark thick daylight factor level line if in compliance with the building code requirement of 2014, and outside if not.

5 The digital visualizations were made in Autodesk 3ds max, Vray rendering, post-processing with Adobe After Effects. The film illustrates an accurate geometrical description of the sun's movements and its effects indoors during 24 hours at the date of 21st of June. The date is chosen in relation to the formulation of the mandatory provision in the Swedish building code. It states that sunlight sometime during the year shall enter into some rooms of an apartment (BBR, 2019, section 6.3 Light, 6.323 Sunlight). It has no precision of time and therefore the optimal day of the year is likely to be chosen by real estate holders when verifying.

6 White walls were chosen for all cases, but floor material was chosen in relation to the architecture of the period.

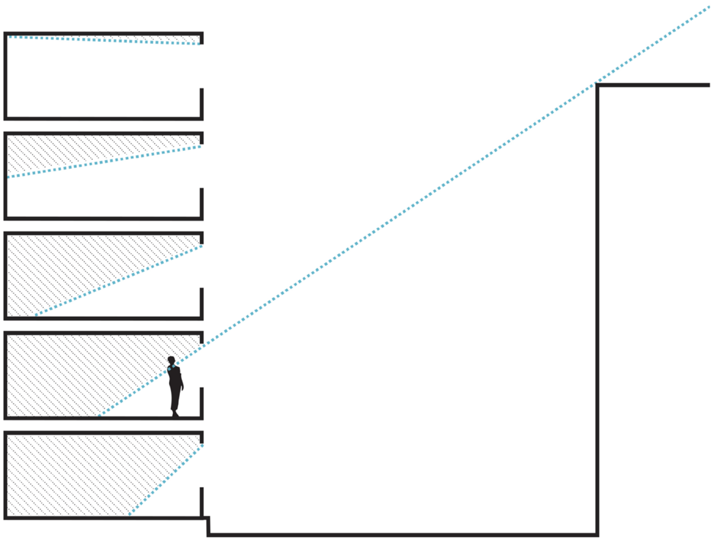
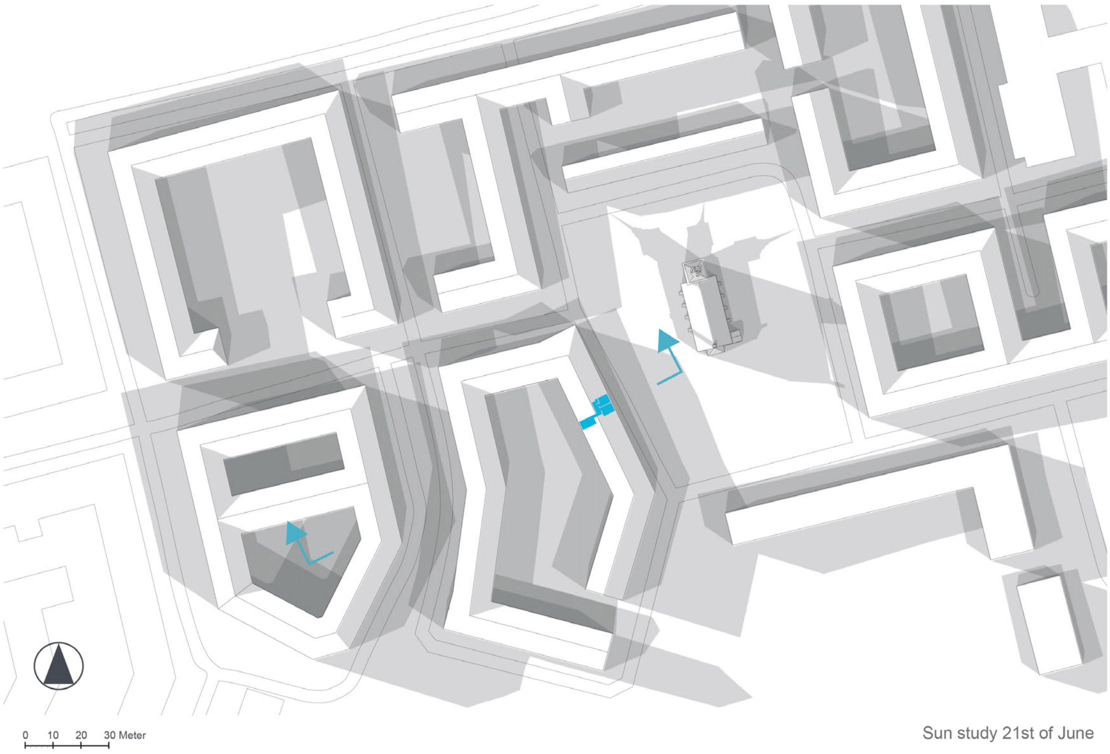


Figure 2
The no-skyline.
SOURCE: MALIN ALENIUS.

Five daylight cases

A case from the 1920s

The first case, Metern Quarter, from 1929, was designed when the first national act on buildings from 1874 still was in force. Additional legislation from 1907 had granted the municipalities autonomy in issuing urban plans that overruled the civil laws governing land ownership (Granath, 2001). In Stockholm, building in the inner courtyards of the blocks was banned, resulting in a new typology of urban planning consisting of large courtyard blocks, called Reform Blocks. These often had a non-uniform shape adjusted to the landscape, which created variety in street views and urban footprints. On the building level, the legislation at the time prescribed limits for building heights at a maximum of 19.5 metres; street widths at a minimum of 18 metres, and indoor room heights at a minimum of 2.7 metres (Byggnadsstadga, 1874, chap. 2 §§ 12-13, chap. 3 §§ 23, 28, 32). The case chosen was designed by Sven Wallinder and Sten Westholm, both acclaimed in Sweden, and the building was within an urban plan developed by the city architect Per Olof Hallman (see Figures 3a, 3b, 3c, 3d). The building's classical façade is in yellow plaster, with repetitive window sizes evenly distributed regardless of the room depths. Balconies only accompany the stairwells. The large courtyard blocks have low obstruction angles (20 degrees), allowing both sun and daylight to reach the façades. The assessed apartment on the first floor receives enough daylight to comply with the 2014 building code in all rooms except for one that is six meters deep. Sequences from the film show how sunlight and daylight enter the west-facing room of the building. In the early morning, reflected light from the façades opposite render the rooms in warm colour, and the direct sun gently enters the windows and illuminates the window niche. During the day, the sunlight moves from the right wall of the room, crosses the floor and reaches the



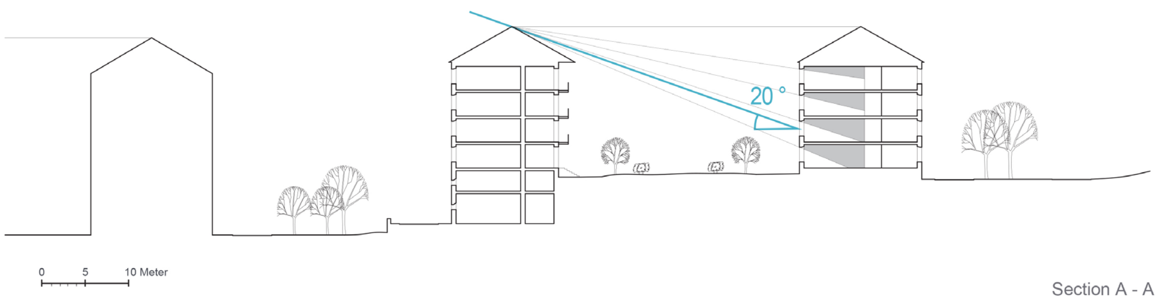


Figure 3 a (top)
A case study from the 1920s; sun study at 9.00, 12.00 and 15.00 on the 21st of June.
SOURCE: MALIN ALENIUS AND MARJA LUNDGREN.

Figure 3 b (below)
Case study from the 1920s; section.
SOURCE: MALIN ALENIUS AND MARJA LUNDGREN.

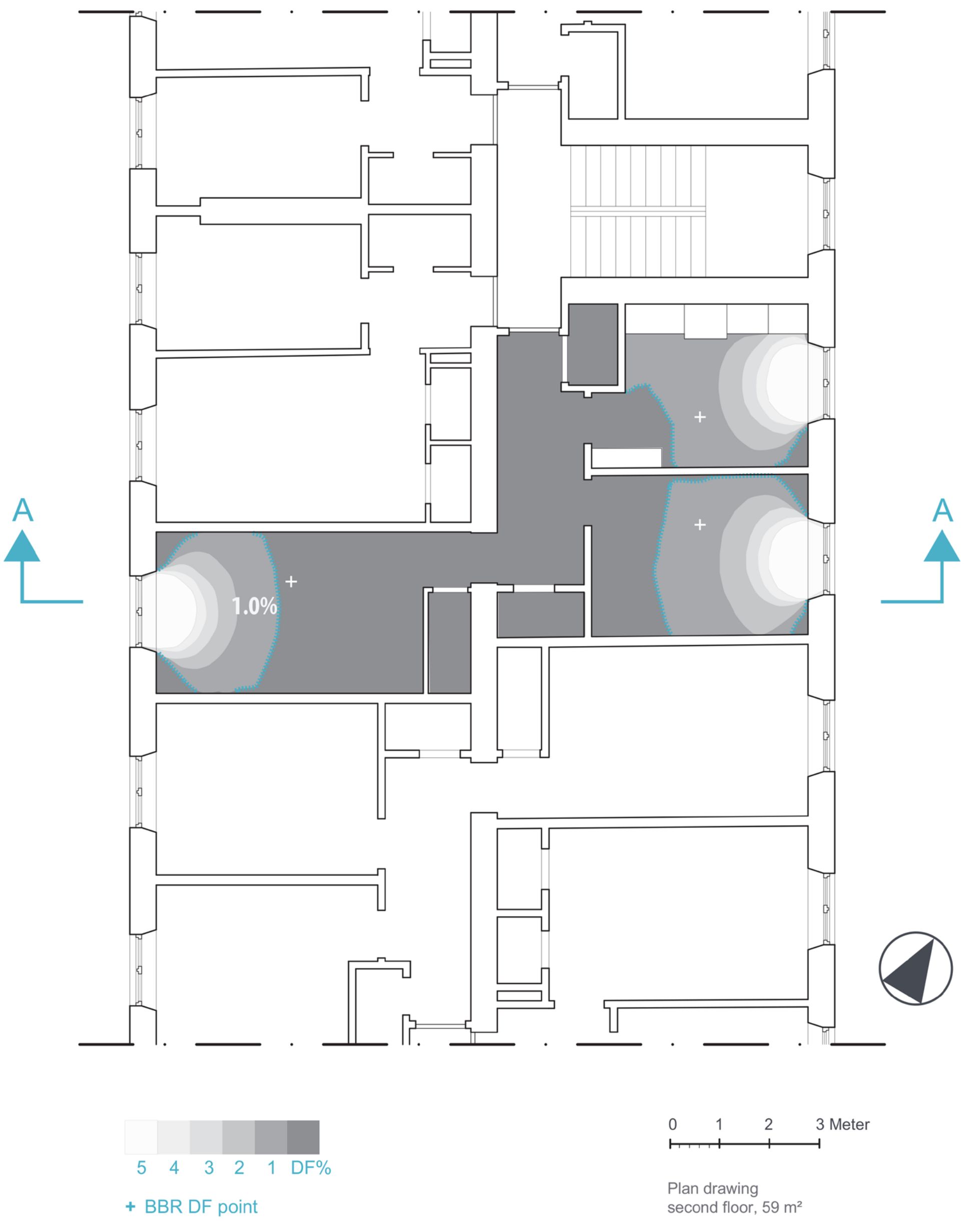


Figure 3 c
Case study from the 1920s; plan.
SOURCE: MALIN ALENIUS AND MARJA LUNDGREN.

A case from the 1950s

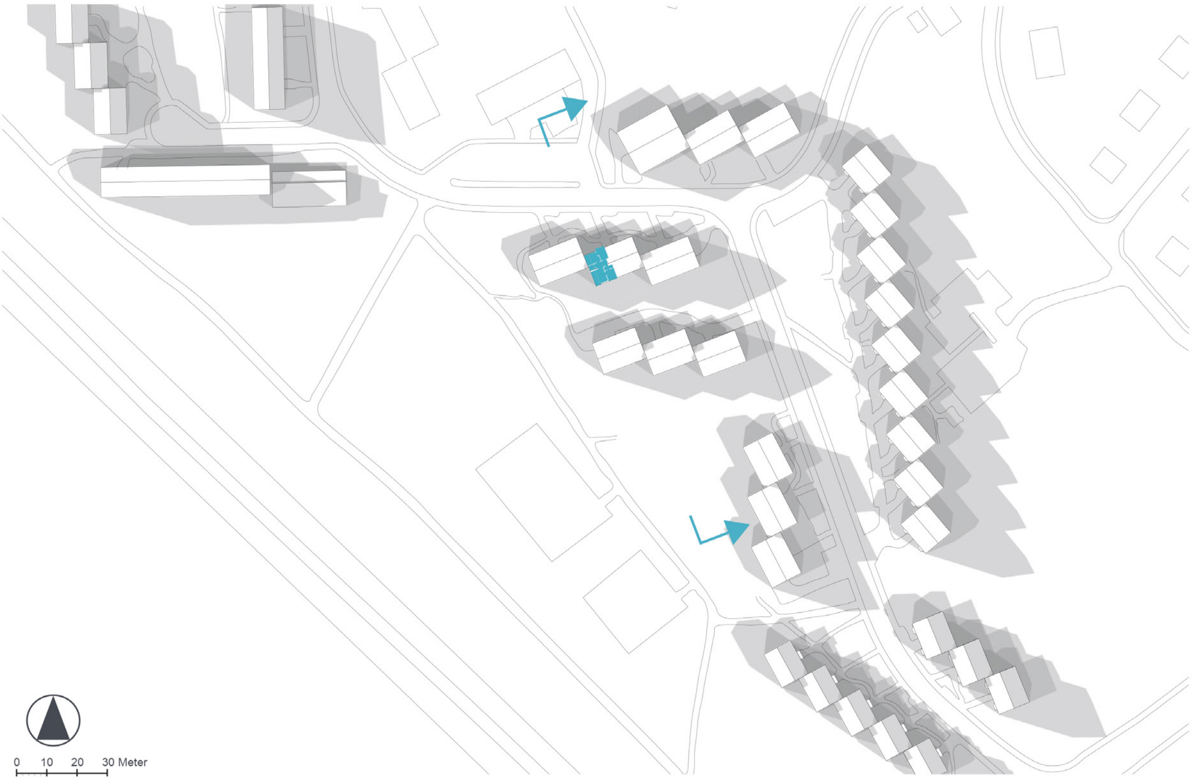
The second case is from Stureby in 1952, when revisions to the National Building Charter from 1931 had turned from prescriptive measures to rules given as geometrical relations. Building heights were now unlimited, provided that the distances between buildings were greater than the building heights. The buildings in Stureby are adapted to the terrain and oriented to solar conditions. New building typologies were developed following the modern movement, and the typology used in this case was called *smalhus*, or "shallow blocks", with a maximum depth

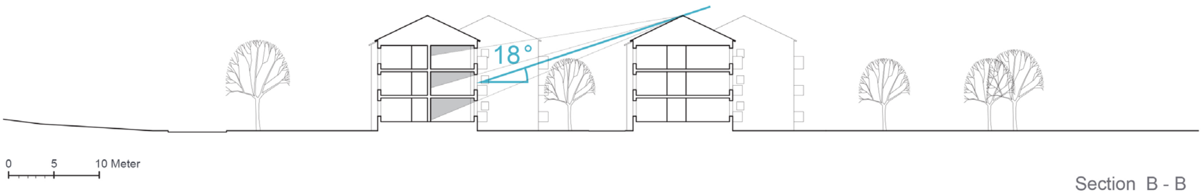
Figure 3 d
Films from five different living rooms showing the dynamic changes in daylight over 24 hours.
SOURCE: MALIN ALENIUS, MARJA LUNDGREN AND TOMAS ZAAR.

of 10-11 metres, six to eight apartments per staircase, and three to four storeys. Designed by the internationally renowned architects Backström and Reinius (see Figures 4a, 4b, 4c, 3d), the façades in Stureby undulated, with balconies set in recessed bays. As the architects stated:

> *In terms of the human factor, it is important how you get light into a room. We have been mocked for all our bay windows, but if it is done well the light comes in in a different way and brings a certain feeling of freedom to the apartments, which is extremely valuable from the residents' point of view [...]* (Enander & Johansson, 1990, p. 23).

Built at a relatively low density, the development complies with the 2014 daylight requirements, both with regard to diffuse daylight and direct sunlight, since sunlight is present year-round. The obstruction angle is low – 18 degrees – and the descriptive geometry analysis of a no-skyline shows a high penetration of daylight into the rooms in the section. The film shows how the interaction of natural light and the undulating façade creates several light-zones (Madsen, 2004) that change during the day within the interior.



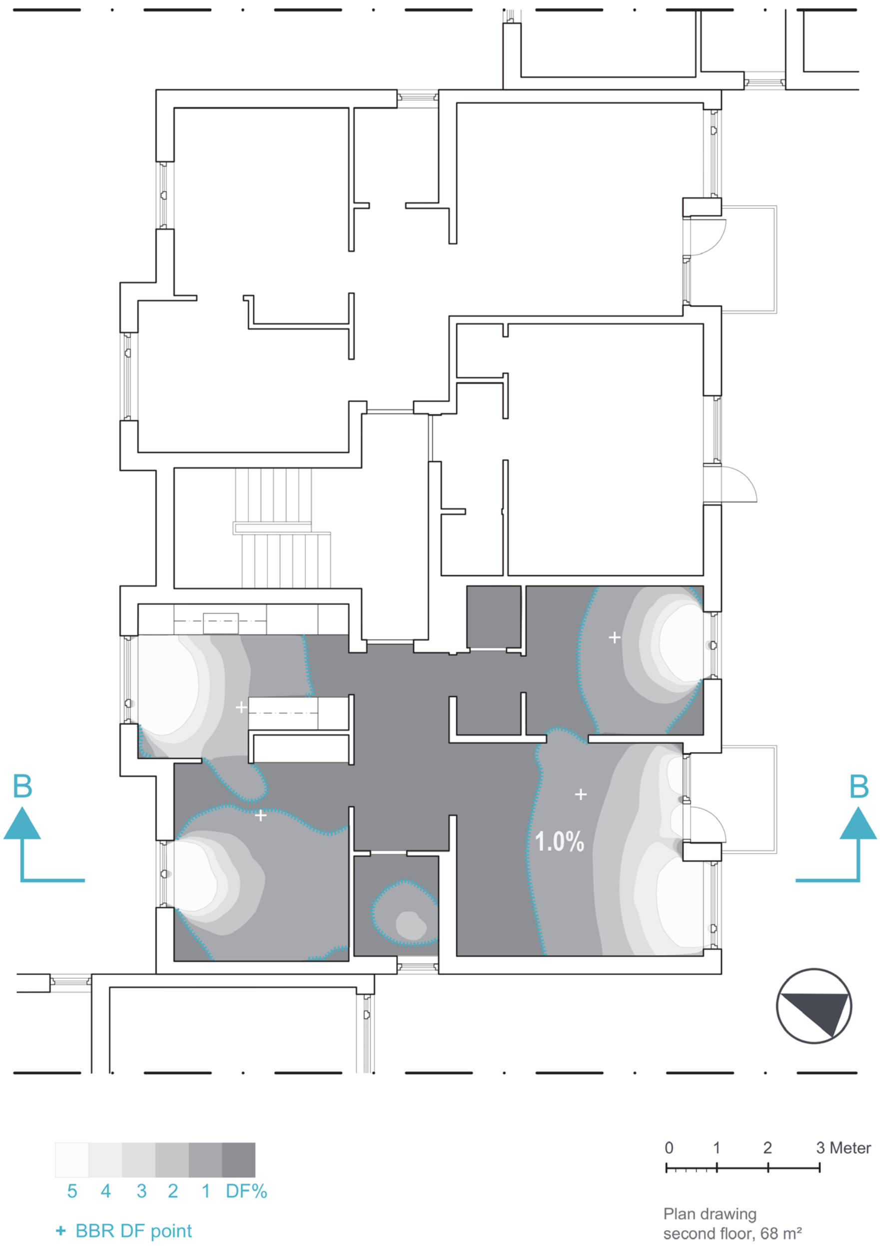


A case from the 1960s

Lagging somewhat after the 1931 charter, the next case from Skärholmen in the 1960s utilises the full potential of this charter regarding free building heights (see Figures 5a, 5b, 5c, 3d). With a new approach to town-planning in the sixties, the traditional town plan was replaced with detached, buildings often formed as rectangular low-rises (*lamellhus*) and high-rises (*skivhus*), slab-blocks of flats. Skärholmen is a good example of the kind of urban settlements produced within *miljonprogrammet* (the "Million Programme", the Swedish state-led initiative to build a million dwellings over a ten-year period). The plan is influenced by the underground, the shopping centre, and the car. The relationship between the white slab building blocks and their topographical placement has direct implications for the availability of light in the apartments.

Figure 4 a (top)
A case study from the 1950s; sun study at 9.00, 12.00 and 15.00 on the 21st of June.
SOURCE: MALIN ALENIUS AND MARJA LUNDGREN.

Figure 4 b (bottom)
Case study from the 1950s; section.
SOURCE: MALIN ALENIUS AND MARJA LUNDGREN.



The buildings are placed in a gentle fan arrangement along the southward facing slope, with low obstruction angles of 10 degrees. All of the rooms in the apartments comply with the 2014 building code. Sequences from the film show that the south-facing full-length balcony with sidewalls effectively shields the living room from direct sunlight in the summer months, although it enters during the colder seasons. The overall light level of diffuse light in the living room is high and drops slowly throughout the day. The even distribution of light indoors stands in contrast to the variations of the outside light scenery seen through the windows.

Figure 4 c
Case study from the 1950s; plan.
SOURCE: MALIN ALENIUS AND MARJA LUNDGREN.

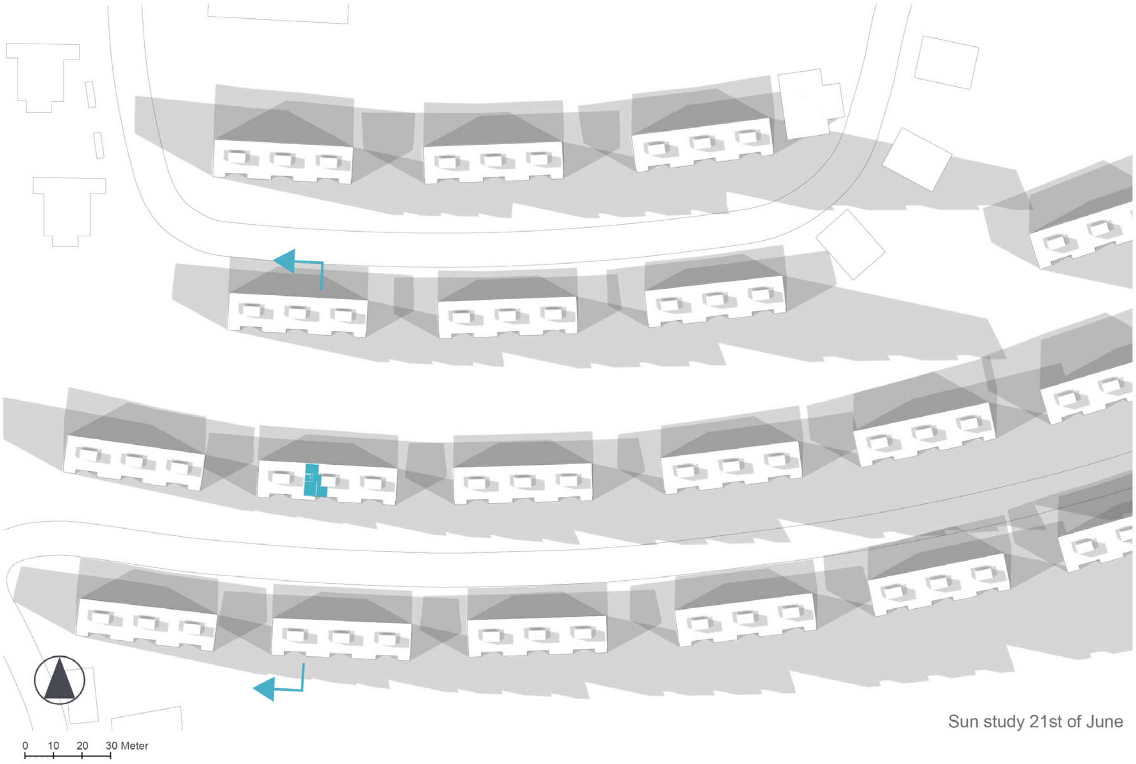


Figure 5 a
A case study from the 1960s; sun study at 9.00, 12.00 and 15.00 on the 21st of June.
SOURCE: MALIN ALENIUS AND MARJA LUNDGREN.

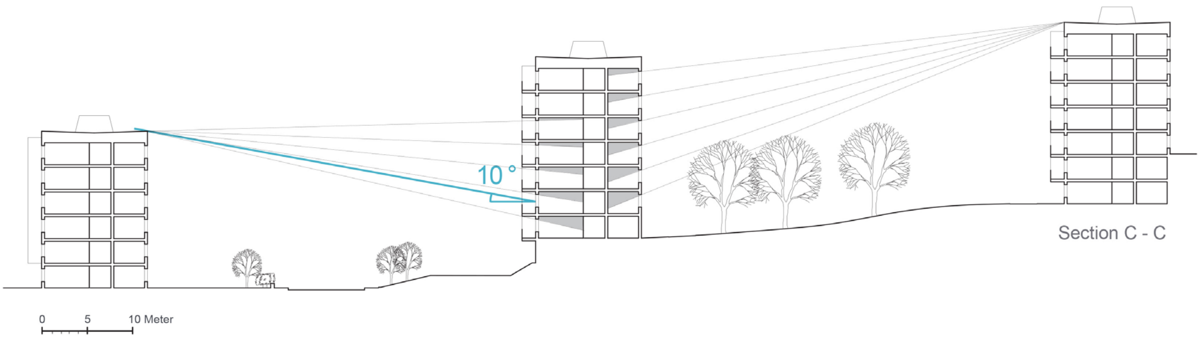


Figure 5 b
Case study from the 1960s; section.
SOURCE: MALIN ALENIUS AND MARJA LUNDGREN.

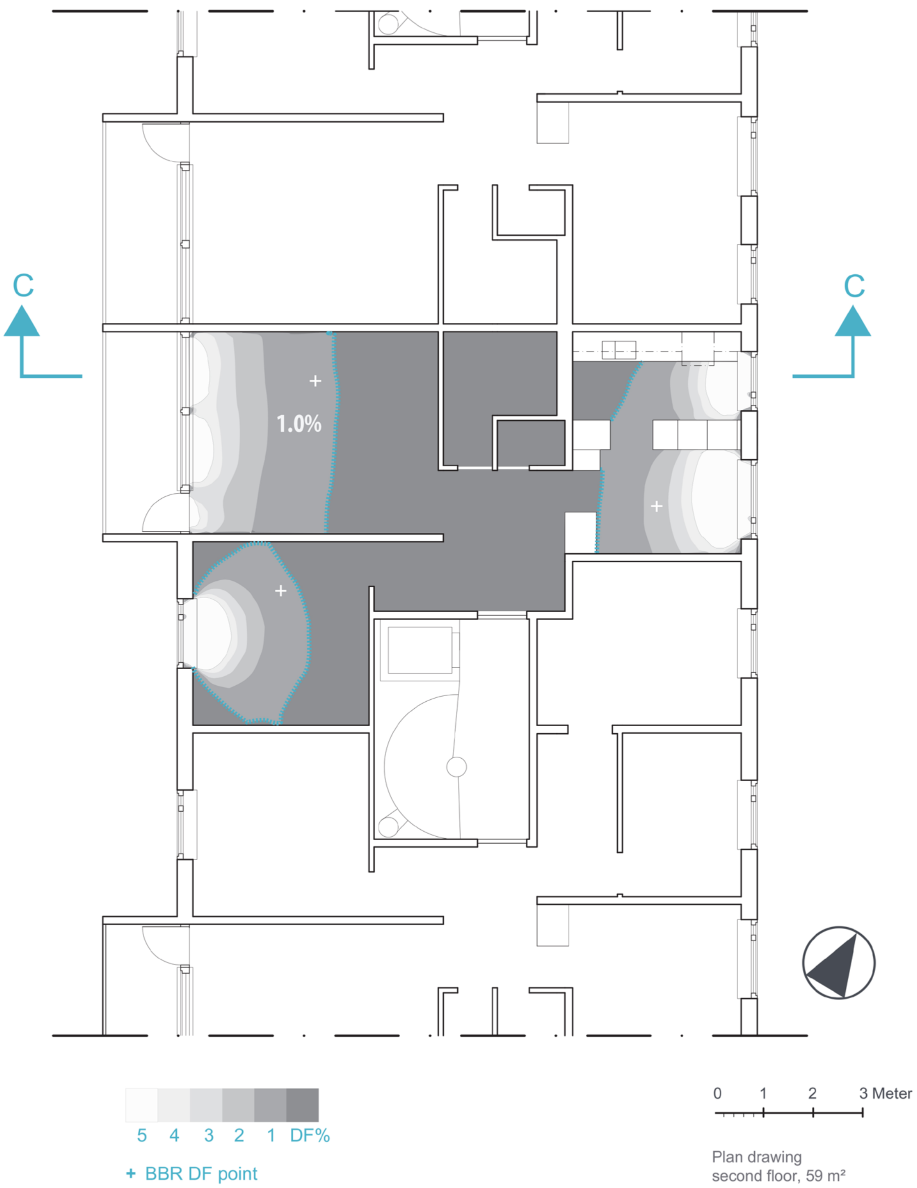


Figure 5 c
Case study from the 1960s; plan.
SOURCE: MALIN ALENIUS AND MARJA LUNDGREN.

A case from the 1980s

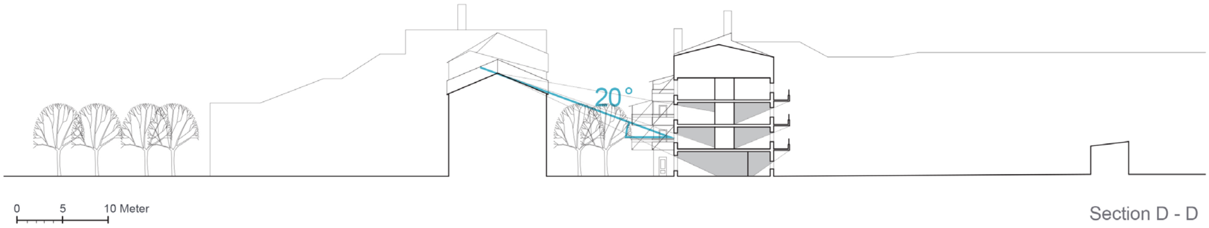
The fourth case in Skarpnäck was designed in the early 1980s, some time after Swedish building codes began the move towards performance-based regulation (Sigge, 2017, p. 78-83; Foliente, 2000, p.13), and after the codes had been adjusted in response to the 1970s oil crisis, which changed energy conservation requirements and generally reduced window sizes and apartment ceiling heights. Daylight factor metrics had been introduced in the regulation by this time. This case, located in the Stockholm suburb of Skarpnäck, was designed by the architectural office associated with Ralf Erskine, Arken Erskine Architects (see Figures 6a, 6b, 6c, 3d). After miljonprogrammet, new architectural trends looked back on traditional city models as a reaction to the Million Programme, building on irregular grid patterns with buildings of varying height. Arken Erskine Architects wrote:

> *Benefits of a variation in housing height of between 2 and 6 storeys: Better sunlight and daylight conditions; an increased feeling of space on grounds and in street areas; the lower buildings help the eye to understand the scale and dimensions of the higher buildings; increased individuality for each building and quarter.*[7]

Drawings and films of this area show that the urban plan allowed for very good daylight and sunlight conditions, with obstruction angles drawn of around 20 degrees, but that the building design does not comply with the 2014 building code, due to the combination of lower room heights of 2.4 meters, the window sizes selected, and the deep balconies and galleries. Film sequences from the living room show that the room has a low overall light level that creates contrasts between the bright light openings and darker walls of the interior room. As sunlight enters the room and moves across the floor and walls, its intensity is contrasted by the room's general lower light level.

7 From an application to the Housing Board by Arken Erskine Architects for an advance notice regarding the Skarpnäcksfältet II development, Arkdes archive.

Figure 6 a
A case study from the 1980s; sun study at 9.00, 12.00 and 15.00 on the 21st of June.
SOURCE: MALIN ALENIUS AND MARJA LUNDGREN.



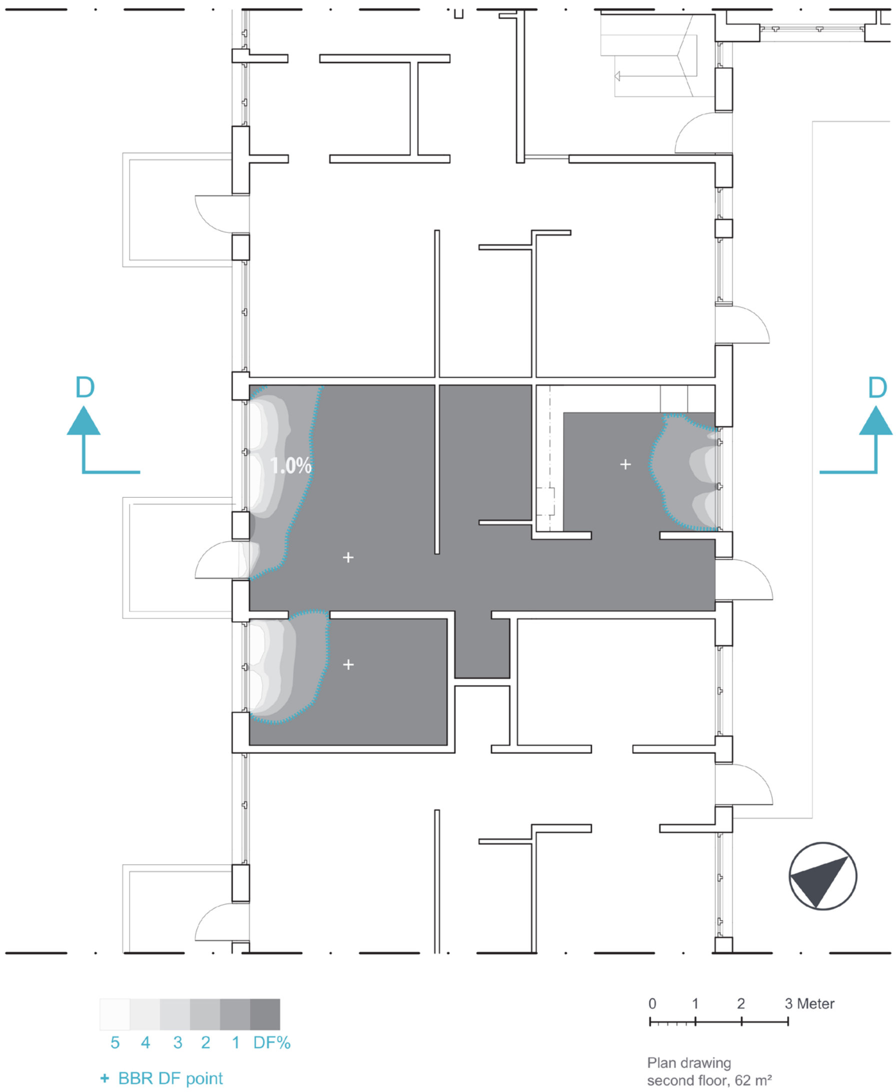


Figure 6 b (top)
Case study from the 1980s; section.
SOURCE: MALIN ALENIUS AND MARJA LUNDGREN.
Figure 6 c (below)
Case study from the 1980s; plan.
SOURCE: MALIN ALENIUS AND MARJA LUNDGREN.

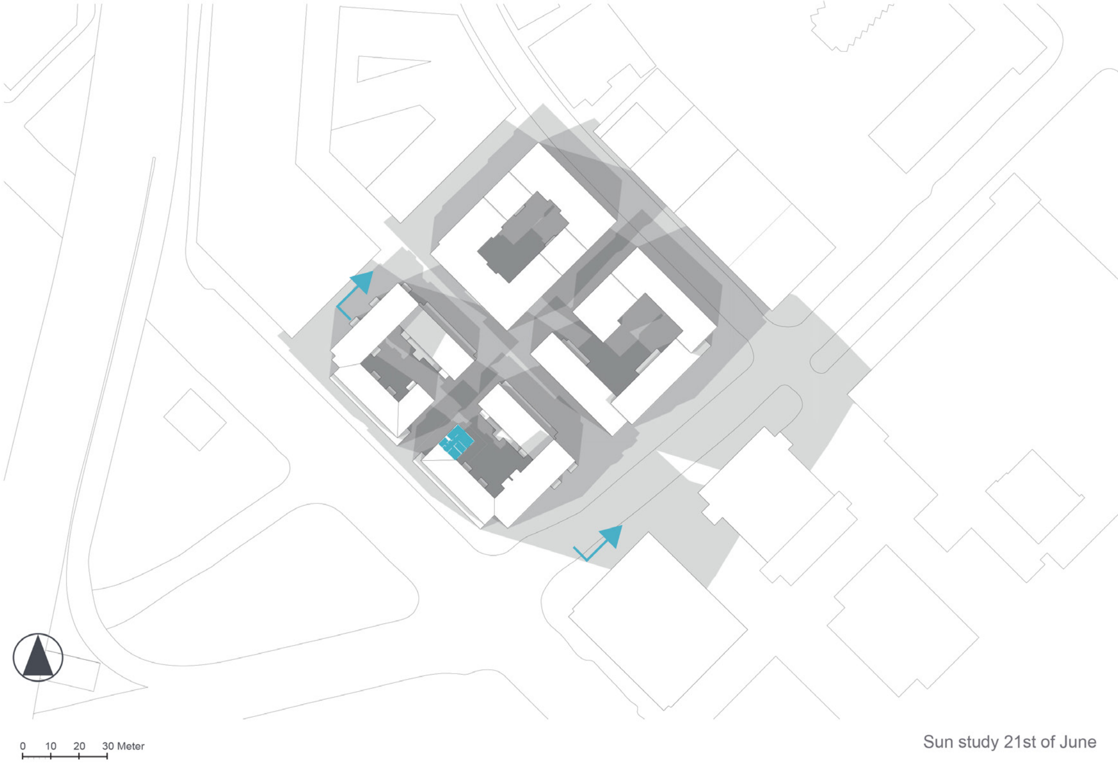
A case from 2010

The fifth and final case in the ArkDes exhibition is from the twenty-first century, when the issue of density had come to the fore, especially in bigger cities such as Stockholm. The dense city block from the 2010s in Hornsberg was designed by ÅWL Architects. The planning architect at the City Council was Charlotte Holst (see Figures 7a, 7b, 7c, 3d). The planning practice of new areas in the outskirts of the dense city is inspired by the inner-city areas of the late nineteenth century (Detaljplan Kojan, p. 20). However, there are radical differences in the architectural and legislative prerequisites of the nineteenth and the twenty-first centuries; with room heights lowered from a minimum of 2.7 meters to 2.4 meters in the building code (although standard building is around 2.5 meters). The project was designed in a period during which the building code lacked a quantitative assessment method for daylight, with obstruction angles over 30 degrees. The desire for density has pushed up building volumes and building depths and reduced street widths and the size of open spaces and lowered standard room heights. In this regime, the choice of materials and the size of windows have become crucial factors for daylight availability. The city-ordained urban plan by Holst for an adjacent area in Hornsberg, at the same time, confirms this:

> *The area will be subject to significant development, equivalent to the densest parts of Vasastan and the Södra Station area. Streets and grounds will only get direct sunlight for short periods of the year. This means indirect sunlight provided by facades will play an important role. It is also imperative that extensions and balconies are restricted in height and spread so that the light in the flats is not further reduced* (Detaljplan Kojan, p. 20).

These building blocks have high obstruction angles on the first floor, around 45 degrees towards the courtyard and 60 degrees towards buildings in adjacent building block. The apartments do not comply with the 2014 building code, which was introduced after its construction. In the dense city canyon, the connection to the open sky changes drastically from the upper floors to the lower floors, and rooms on the lowest floors are dependent on reflected light from the façades opposite them and from the ground materials in the courtyard. Larger glass areas could have increased the access to daylight, but this was not possible at the time due to the building code energy demands and a lack of other, alternative arrangements to meet energy requirements. The film in this case illustrated two parts of a common living room, a dining area and a kitchen. The dining area is located in the north-western corner of the room, while the living room window faces southeast. Sequences from the film show that the dining area and living room receive some direct sunlight at the height of summer. Besides this, the southeast window of the living room area is illuminated primarily by exterior reflected daylight.

The white walls of the opposite façades create fully diffused light that lack contrast both in colour and light. The space is modulated in the same way throughout the day as the light level slowly falls.



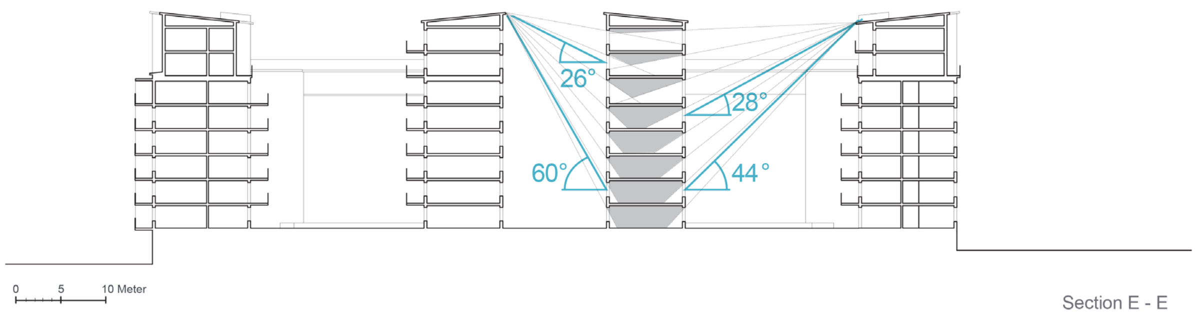


Figure 7 a (top)
A case study from the 2010; sun study at 9.00, 12.00 and 15.00 on the 21st of June.
SOURCE: MALIN ALENIUS AND MARJA LUNDGREN.
Figure 7 b (below)
Case study from the 2010; section.
SOURCE: MALIN ALENIUS AND MARJA LUNDGREN.

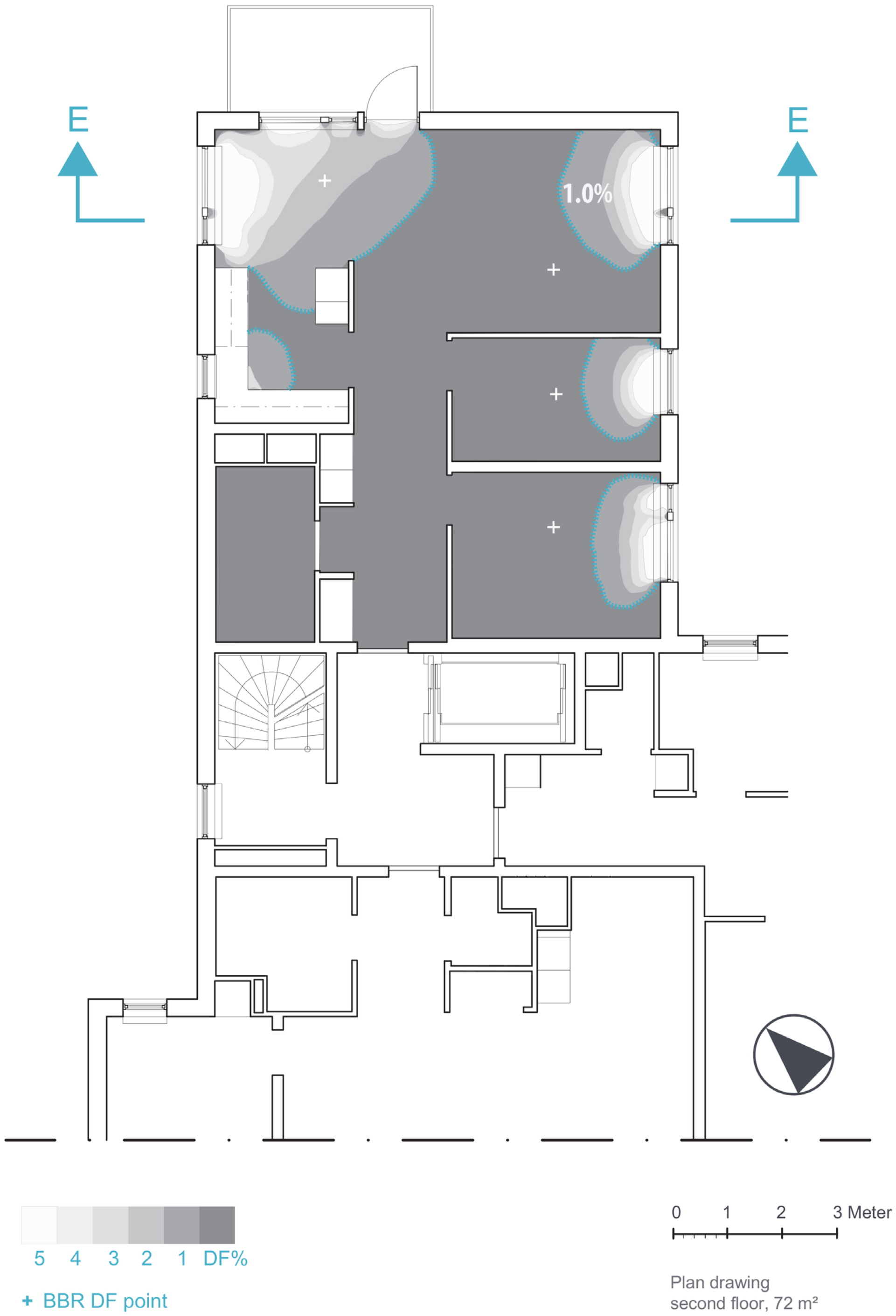


Figure 7 c
Case study from the 2010; plan.
SOURCE: MALIN ALENIUS AND MARJA LUNDGREN.

Comparing with a parallel numerical analysis of several cases

The numerical analysis of daylight factor metrics was carried out by Iason Bournas and Marie-Claude Dubois. The numerical analysis aimed to demonstrate a conclusive quantitative analysis, and in this section, it is used as a comparison to the five cases with regard to two aspects. The first aspect relates to the identified daylight design parameters found on the urban and building design level, and the second aspect is the daylight factor results in relation to the 2014 building code daylight requirement.

According to Rolf Johansson, a Swedish researcher of case study methods, there are two principal forms of case studies: the first focuses on the specific case itself; that is, the intrinsic case study, while the second form is driven by an aim to reach general knowledge; that is, the instrumental case study (2000; 2003). The intrinsic case study is typical for studies in architectural history. The instrumental case study, which concentrates on specific parameters or variables reoccurring in several cases, is very common in environmental science studies relating to architecture and energy. There are also case studies located somewhere in between, in which the intrinsic case study method and the will to generalize coexist.

The five exhibition cases in this article can be positioned in between the two modes of case study – the intrinsic and the instrumental – with an aim to reach applicable architectural methods to design with and assess daylight in architecture. The numerical analysis carried out by Dubois and Bournas is an instrumental case study based in building science with an aim to establish general knowledge (Bournas, Lundgren, Alenius & Dubois, 2017; Bournas & Dubois, 2018).

The numerical analysis derives information on daylight factors in typical Swedish residential multi-family buildings from 1926-1991 in relation to the 2014 daylight factor recommendation in building code (Bournas et al., 2017; Bournas & Dubois, 2018). The existing building stock is analysed through advanced daylight calculations[8] of 54 buildings consisting of 10 888 individual rooms, out of which 35 buildings and 8 573 rooms were selected by the authors of this article (Bournas et al., 2017).

Interestingly regarding the first aspect of comparison is that, the exhibited cases and the numerical analysis show correlating results regarding both the key relationships between the daylight factor metric and urban and building geometries and the daylight performances during the different decades. In the conference paper from the numerical analysis, it became apparent how the window sky exposure factor, a three-dimensional (3D) sky view[9], is a key urban design parameter affecting the daylight factor (Bournas et al., 2018). As shown earlier, the exhibited five cases also demonstrated how the two-dimensional (2D) obstruction

8 The digital calculation was based on three-dimensional digital environments of the buildings and its surroundings, and a single simulation was performed per room using Radiance simulation engine via Honeybee in the visual programming environment of Grasshopper (Bournas et al., 2017).

9 The sky exposure factor (SEF) is the percentage of the sky that is visible from a surface. The window sky exposure factor is the percentage of sky visible from a window surface. This is equivalent to a solid angle calculation from a point on the window surface to the sky dome. The sky dome in the numerical analysis is a Tregenza Skydome where each patch is subdivided for times for higher accuracy (Bournas et al, 2017, p. 992).

angle at an urban level, due to obstructions from other buildings, is the key component affecting daylight availability. Both the sky exposure factor and the obstruction angle address the amount of visible sky that a window "can see" and its effect on available daylight indoors. While this is by no means ground-breaking news and although it has been presented in British guidance before, it is a relevant reminder to the architectural community (Littlefair, 2011). In short, both the exhibited cases and the numerical analysis also indicate that window sizes and room depths are key features of the design on the building level.

Additionally, the five exhibited cases show how the obstruction angle on a building level – due to obstructions such as balconies and galleries – will greatly impact daylight availability. This has not been addressed specifically in the numerical analysis.

The second aspect of comparison concerns the daylight factor results of the different decades in relation to the present Swedish building code. Tables of the compliance with 2014 building code is presented in the numerical analysis for each decade on room, apartment and building level (Bournas & Dubois, 2018). In the sample in its entirety, 63 per cent of the rooms are in compliance with the code. On a building level however, only 6 per cent comply with the regulation, i.e. 3 buildings out of 54.[10] The three buildings that complied with the regulation in the numerical study were from the 1950s, and 93 per cent of the rooms of the era were in compliance (Bournas & Dubois, 2018, p.15).

10 The numerical analysis also addressed the relation between different daylight factor metrics, and the findings were showed a correlation between the daylight factor point of 1 per cent, the daylight factor average of 2 per cent, and the median factor point of 1 per cent (Bournas & Dubois, 2018, p. 16).

In both the exhibited cases and the numerical analysis, the 1950s outperforms other periods. This is a period during which the urban planning follows the restrictions of the parametric relations between distance and height dictated by the planning act from 1931. This can be compared with the decade that performed the worst in the numerical analysis – 1981–1990; during this period, a total of 24 per cent of the rooms met the requirement on the room level, and none of the apartments or buildings met the building code requirements. Nor did the apartment case from the 1980s that was included in the exhibition comply with the 2014 building code. During this period the building code was expressed though the daylight factor metric.

The numerical analysis also shows apartment compliance over 50 per cent in the period of the 1940s. One could argue that building regulations between 1931 and 1960 were quite straightforward from an architectural point of view, with a parametric relationship, and that there were no other constraints (e.g. energy) to make fulfilling the daylight requirements difficult. In the 1980s, on the other hand, a combination of economic crisis, energy crisis and an abstract building science metric that was quite time-consuming to calculate at the time, worked against an easy fulfillment.

Daylight factor metrics easily accessed through descriptive geometry

In his article on the mathematization of daylighting, Alan Lewis inquired into the practice of daylight building science standards and norms in architectural design during the period of 1956-1992 and concluded that

> *[...] quantifiable standards are meaningful only where compliance is demonstrated through measurement, or where architects know how to meet the standards without resorting to measurements (2017, p. 1172).*

His recommendation is therefore that when future daylighting standards are developed, they should be translated into simple principles that architects can use (Lewis, 2017, p. 1172). Lewis' interviews also showed that those who had learned the theoretical background of the daylight factor said that they had gained knowledge that they utilised when designing, although they avoided carrying out the manual calculations of daylight factor (Lewis, 2017, p. 1170). The aim with the five architectural case studies was to give architects tools and knowledge to understand how to assess design solutions of existing and new cases through easy descriptive geometry. We argue that the basics of the daylight factor unfold in geometric relationships that are easy for architects to use. The obstruction angles provide direct information on the urban level that can in turn give information about the freedom or challenges that lie ahead on the building design level.[11] The five architectural cases in this article map the geometrical parameters that are crucial for the relation between the urban site (scale and design) and the building (façade, balcony and window design) and room design (indoor room height, room depth and form) in relation to consequences for daylight availability. The architect and planner have a great number of variable parameters; their interrelation and the resulting obstruction angle of this geometry are what can indicate to the architect the daylight challenges at hand. The scalable geometric figure serves as an intermediary of a mathematical formula and a drawing, allowing the architect to work with a complex whole in which all parameters are closely interrelated. In early planning stages on an urban level, a two-dimensional obstruction angle is enough for an architect to assess the situation for a relatively homogenous block. Architects could use their knowledge from historical, contemporary, and their own cases to perform a more thorough analysis using descriptive geometry via the architects' drawing and sections. The architectural representations of the five cases inform the architect, as does the tradition of precedence and repertoire. A greater quantity of analysed cases will give the architect a greater repertoire of cases, situated within the complex spatial environment to which an architect needs to relate. As the unfolding of the daylight metrics has shown the obstruction angles in 2D or sky exposure factor in 3D –depending on complexity of the urban plan[12] – are a vital tool for determining whether or not the urban plan allows for easy measures to gain access to daylight according to the

11 Additionally, the no-skyline is also a very illustrative way of informing the non-professional regarding the relation between direct light and reflected light in a specific room.

12 Obstructions angles in sections, as in two dimensions, is appropriate in urban plans with homogenous building heights. When the urban plan presents a more complex relation, for example by varying building heights, three-dimensional sky exposure factors (SEF) and digital computation can be needed.

regulative levels. On an urban level, our general conclusions are that if the obstruction angle is inferior to 30 degrees, the building design will determine whether or not the rooms will comply with the legislation, and if the obstruction angle is above 45 degrees, the interplay between façade materials, reflections and building design – especially room heights and window sizes – will be of importance.

The inspection of daylight comes too late in Swedish building regulation

The Swedish Planning and Building Act does not specifically address daylight. Instead, daylight is treated as a technical requirement in the building code (BBR, 2019, 6:322, p. 98). The planning and building process is regulated from comprehensive planning, urban and design stages, and through the control of the detailed plan, the building permit, the starting permit and finishing permit. The building code daylight compliance is checked before the starting permit is issued. In the case of Sweden, this has resulted in a control of daylight at a late stage – long after the urban plan and building design phase. We argue that this is first and foremost a consequence of the lack of explicit requirements in the urban and detailed planning stage with regard to checking daylight availability, and that secondly, the performance requirement in the code is detailed through a metric whose theoretical and geometric base is seldom illustrated to the planning or architectural community. The very early planning stages would benefit from simple rules based on a fundamental understanding of the interrelation between urban and building design and daylight availability, such as those based on obstruction angles and no-skylines shown in the material of this article. The possibility to comply with the performance requirement later in the process would certainly benefit from early geometrical assessments of the detailed plan. As daylight availability is the result of relationships between the interior room and the exterior urban setting, as demonstrated in the obstruction angles, this is necessarily an early urban control point. The specific daylight factor metric can then be used as a verification through calculation before the building permit. The calculations of the specific daylight factor of a room are also an effect of the building design, such as façades, balconies, etc. that should preferably be checked before issue of the building permit.

The need for architectural methods in relation to building science metrics

Since the post-war period, standards and regulations have developed metrics based in building science in order to assess legislative goals on daylight (Lewis, 2017). Initiated in 1967, the Swedish building code has undergone a transformation from issuing prescriptive requirements, by stating solutions, towards performance requirements, by stating expected building characteristics (Svensk Byggnorm, 1967, p. 519). The prescriptive requirement of an urban section from 1874 addressed fire safety, ventilation, and daylight altogether. Performance requirements tend to address one characteristic at a time. In a National Swedish Building Research Report from the 1970s on how to write and assess performance requirements, the focus was on what the researcher Jens Knocke defined as technical and non-artistic aspects (1970). Since 2004, the National Board of Housing, Planning and Building has stated in internal guidelines that performance requirements should not limit choices in design, material and methods (Lundgren, 2016, p. 126). We argue that a division in technical and design characteristics of a building that can be found in current Swedish Planning and Building Act (Plan- och bygglagen, 2010) is a chimera, and that performance requirements labelled as technical and expressed in terms of abstract maths or building physics need to be assessed from a form perspective and supported by architectural methodology and representation. The architectural research community's engagement in developing architectural knowledge on architectural expression in relation to environmental control (experienced comfort in relation to building physics, resource use and emissions) is scarce. This is a contrast to the large volume of building science research articles on the same subjects, where architecture is described in generic terms, which results in guidelines, metrics and digital modelling methods that ignore individual differences.[13]

Quantitative performance requirements in building codes often are based in building science; thus, an interesting question is how to inquire into and disseminate such a requirement in another tradition. The building science representations of the numerical study relate to a tradition that illustrates the abstractions and generalisations of real-world phenomenon (Lewis, 2017, p. 1156). This brings this discussion to the relationship between context-independent knowledge, i.e., generalised knowledge and context-dependent knowledge from cases and particularities of real-world phenomena (Flyvbjerg, 2006). While the Arkdes exhibition presented the daylight factor through architectural representational case study material to show the particulars of each case and give the architect an understanding of the correlation of spatial relations to daylight, the numerical study presented the trends of daylight availability in the twentieth century, forming new general and theoretical knowledge on daylight metrics. The numerical performances based on calculation, today often derived from digital calculation, are not always transparent for a planner or an architect. The daylight exhibition reviewed in this article was in itself an act to remedy the problem of the division between different representational methods that emerges between the conventions of architectural design and those of building science. The architectural case study series illustrates daylight levels in architectural representations, with obstruction angles, no-skylines illustrated in sections, and the daylight factor metric in plans, along with visualisations

13 A broad search for the daylight factor metric, evident worldwide in building regulation and standards, in the body of texts of articles in KTH Royal Institute of Technology's collected databases. The search returned 1 386 online hits in 17 leading journals. Of these hits, 1 143 were from between 2000–2018 (51 articles in *Architectural Science Review*). The subject Engineering returned 367 hits, Daylight 238, Buildings 216, Architecture 165, and Architecture Engineering 140 hits, and so on in further building science subjects. Looking into Architecture, Alan Lewis' article in *Journal of Architecture* is the second most relevant result returned (altogether 2 articles from the *Journal of Architecture* among the 165 hits). A broad range of leading journals was represented among the 165 hits on the subject architecture. A complementary search in the database Jstor returned 77 hits, six of which were from 2000–2018; the majority of those (four) are from the subject of architecture and architectural history.

of interior daylight and sunlight in films to support a relational understanding between building science and architectural representations in the specific cases. We argue that the use of the architectural case study methodology on environmental concerns – such as the example daylight – in architecture is necessary to create new architectural knowledge related to environmental control and building regulation. As design is an act that involves many competences and many kinds of knowledge, both context-dependent and context-independent knowledge will inform the process. We argue in favour of not letting a context-independent understanding of issues regarding performance requirements take precedence. Instead, performance requirements need to be disseminated both as cases in a context and through general theory.

Acknowledgements

With great thanks to Iason Bournas and Marie-Claude Dubois for inviting us to participate in the paper referred to for the numerical analysis. Funding from the KTH Royal Institute of Technology, School of Architecture and the Built Environment, White Arkitekter AB, ARQ –body of two foundations established by White Arkitekter AB, and Bertil & Britt Svenssons' Foundation of Lighting Technology – are all gratefully acknowledged.

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