Daylight compliance of multi-dwelling apartment blocks

Design considerations, evaluation criteria and occupant responses

Bournas, Iason

2021

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Bournas, I. (2021). *Daylight compliance of multi-dwelling apartment blocks: Design considerations, evaluation criteria and occupant responses*. [Doctoral Thesis (compilation)]. Department of Architecture and Built Environment, Lund University.

Total number of authors:
1

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

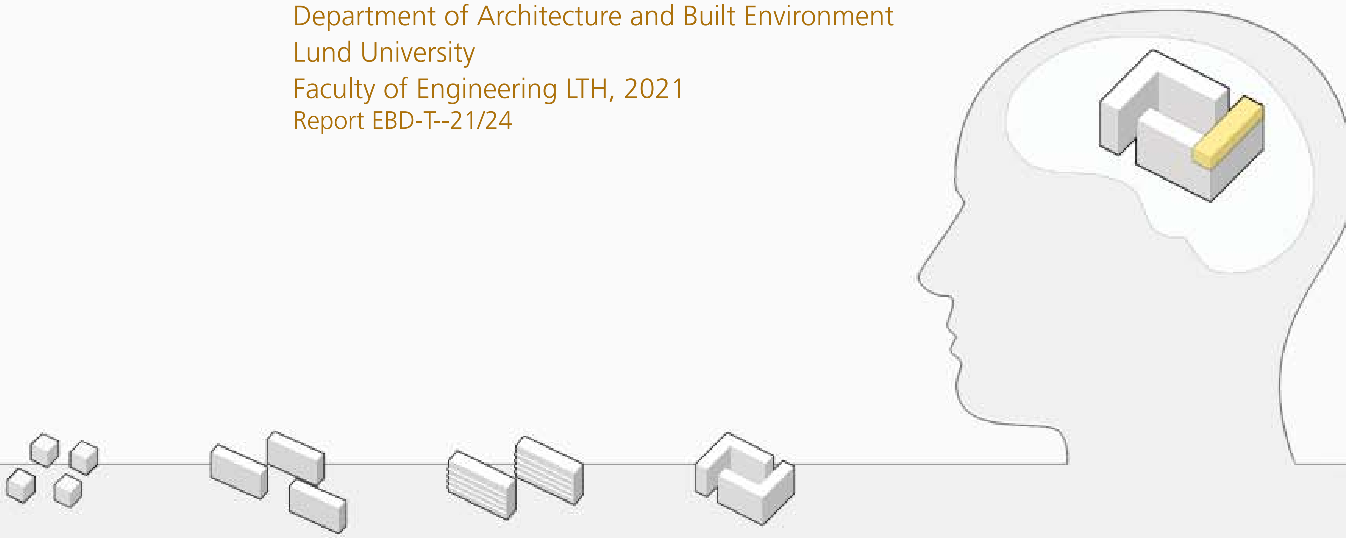
Daylight compliance of multi-dwelling apartment blocks

Design considerations, evaluation criteria, and occupant responses

Iason Bournas

Division of Energy and Building Design
Department of Architecture and Built Environment
Lund University
Faculty of Engineering LTH, 2021

Report EBD-T--21/24



1666

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 116 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 8 300 employees and 44 000 students attending 272 degree programmes and 1 700 subject courses offered by 69 departments.

Division of Energy and Building Design

Reducing environmental effects of construction and facility management is a central aim of society. Minimising the energy use is an important aspect of this aim. The recently established division of Energy and Building Design belongs to the department of Architecture and Built Environment at the Lund University, Faculty of Engineering LTH in Sweden. The division has a focus on research in the fields of energy use, passive and active solar design, daylight utilisation and shading of buildings. Effects and requirements of occupants on thermal and visual comfort are an essential part of this work. Energy and Building Design also develops guidelines and methods for the planning process.

Daylight compliance of multi-dwelling apartment blocks

Design considerations, evaluation criteria, and occupant responses

Iason Bournas

Doctoral Thesis

Keywords

Daylight, electric lighting, policy, regulation compliance, simulation, questionnaire, daylight metrics, perception, brightness, user preferences, urban density, block typology, room geometry, room function, room orientation.

Lund University, Faculty of Engineering, Lund 2021.
The English language was corrected by: Leslie Walke
Layout: Hans Follin, LTH, Lund.
Cover illustration: Iason Bournas

Printed by E-husets Tryckeri, Lund 2021

Report No EBD-T--21/24
Daylight compliance of multi-dwelling apartment blocks. Design considerations, evaluation criteria, and occupant responses.
Department of Architecture and Built Environment, Division of Energy and Building Design, Lund University, Lund

ISSN 1651-8136
ISBN 978-91-85147-64-9

Lund University, Faculty of Engineering
Department of Architecture and Built Environment
Division of Energy and Building Design
P.O. Box 118
SE-221 00 LUND
Sweden

Telephone: +46 46 - 222 73 52
Telefax: +46 46 - 222 47 19
E-mail: ebd@ebd.lth.se
Home page: www.ebd.lth.se

Abstract

This thesis examines the daylight compliance of residential spaces, in particular apartments in multi-dwelling building blocks, and provides knowledge that may prove useful for the development of future daylight criteria for dwellings. The implications of design choices on daylight compliance of spaces and the effect of daylight criteria on the level of compliance are at the core of this work. Daylight simulations were performed to evaluate a large sample of representative apartment buildings according to past and present daylight criteria. Self-administered questionnaires were also used to investigate occupant preferences and subjective impressions of daylight conditions in the dwellings. The simulations and questionnaires divide this work into two parts, which are connected on the basis of the same study object: multi-dwelling buildings.

The first part includes a review of daylight regulations in Sweden from the time the term "daylight" first appeared in 1960. It proceeds with compliance testing results for a large sample of multi-dwelling blocks, evaluated according to the current Swedish daylight compliance criteria. Several criteria commonly used internationally are assessed for the same spaces, to evaluate compliance differences when using different criteria. The review concludes that there has been no significant progress in Swedish daylight regulations since 1975, when the basis for the current daylight factor criterion was first formulated. It also argues that the current geometric criterion has limitations due to spatial implications deriving from its formulation. The compliance testing results indicate that Swedish daylight criteria have not been successful in safeguarding daylight access for residential spaces historically, especially in denser urban areas, perhaps because they were expressed as "general recommendations" instead of "mandatory provisions". To this end, several buildings built prior to the introduction of daylight criteria, and built only by architectural intuition, perform better than regulated buildings. A more detailed assessment of the investigated rooms using additional criteria indicated which building types perform better overall, which geometric attributes are more significant for compliance, and the effect of urban density on compliance.

The second part includes results from a questionnaire survey carried out in the city of Malmö, the third largest city in Sweden. The questionnaires were distributed in buildings of the same block typologies as the buildings evaluated via simulations in the first part of this research. This second part concerns daylight perception, electric lighting use, and occupant preferences with respect to daylighting among room types. The questionnaire rating scales were validated for their suitability as a form of measurement for daylight surveys. The reported electric lighting use was compared between different room types, geometries, and facade orientations to evaluate whether there is less use of lighting in rooms with specific characteristics. The relation between reported daylit area and electric lighting use was analysed to assess whether daylight availability can yield reductions in electric light use, to what extent, and under which conditions. The survey also revealed clear occupant preferences, indicating the room types where daylight availability is prioritised.

Contents

Acknowledgements

This research was carried out with the financial support provided primarily by the Swedish Energy Agency, to which I am indebted. I hope that the outcome lives up to their expectations. I also want to express my gratitude to ARQ and Arkus Stiftelsen for financial contributions necessary for the questionnaire survey carried out for this research.

There is no doubt that I am most indebted to my supervisor Dr. Marie-Claude Dubois, who trusted me with this task and supported me throughout this long process. I am also grateful to my co-supervisor, Dr. Thorbjörn Laike, for his crucial remarks and comments, and for encouraging me to look deeper into aspects of environmental psychology.

The following all deserve mention. Dr. Henrik Davidsson, who filled the gap when there were no PhD students with whom to discuss methods and findings, and for being a Swiss Army knife taking care of pyranometer calibrations, communications with occupants and text translations among other things. Ludvig Haav, Marwan Abugabbara and Malena Bengtsson who helped with Swedish and Arabic translations required for the questionnaire survey. Olof Wiese who provided the precious space and mounting equipment to install pyranometers in a very useful location. Andreas Eggertsen Teder who patiently contacted occupants and arranged visits to their residences. All the occupants who gave their responses, which were crucial for the survey findings. Dr. Todor Stojanovski who guided me in my initial steps within the realm of GIS data. Dr. Kevin Houser who was patient and kind enough to share crucial knowledge during maybe the most thorough review among the published papers. My brother, Odysseas Bournas, who provided the security that only a real computer whiz can provide when dealing with software customisations and programming needs. My co-student during my Architecture studies, Ioannis-Antonios Moutsatsos, who always challenged the questions asked, and retained the element of architectural design within the scope of this thesis. Dr. Harris Poirazis who helped me navigate my way through the final stages of this project and taught me to focus on the big rocks first, on what really matters.

Finally, I have to give credit to Danai for her patience and understanding, as well as for being there as both a project manager and a lighting

designer. She helped me stay on track, and she helped me keep in mind what type of daylight is actually useful for real residential buildings.

List of publications

Appended publications

All articles are published in peer-reviewed journals. The peer-review was single-blind for papers I-V, and double-blind for paper VI. Papers I, III, V & VI are published under open access licences.

Paper I: Bournas I. (2020). Swedish daylight regulation throughout the 20th century and considerations regarding current assessment methods for residential spaces. Building and Environment. 191: 107594. doi: https://doi.org/10.1016/j.buildenv.2021.107594

Paper II: Bournas I, Dubois M-C. (2019). Daylight regulation compliance of existing multi-family apartment blocks in Sweden. Building and Environment. 150: 254-265. doi: https://doi.org/10.1016/j.buildenv.2019.01.013

Paper III: Bournas I. (2020). Daylight compliance of residential spaces: Comparison of different performance criteria and association with room geometry and urban density. Building and Environment. 185: 107276. doi: https://doi.org/10.1016/j.buildenv.2020.107276

Paper IV: Bournas I, Dubois M-C, Laike T. (2019). Perceived daylight conditions in multi-family apartment blocks – instrument validation and correlation with room geometry. Building and Environment. 169: 106574. doi: https://doi.org/10.1016/j.buildenv.2019.106574

Paper V: Bournas I, Dubois M-C. (2020). Residential electric lighting use during daytime: A field study in Swedish multi-dwelling buildings. Building and Environment. 180: 106977. doi: https://doi.org/10.1016/j.buildenv.2020.106977

Paper VI: Bournas I. (2021). Association between perceived daylit area and self-reported frequency of electric lighting use in multi-dwelling buildings. LEUKOS. (2021) 1-20. doi: https://doi.org/10.1080/15502724.2020.1851606

The author's contribution to the appended publications

Paper I:	The author designed and performed the study, and wrote the article.
Paper II:	The study was designed by the author and Marie-Claude Dubois. The author collected and analysed the data, processed the results, and wrote the article.
Paper III:	The author designed and performed the study, and he wrote the article.
Paper IV:	The study was designed by the author and Marie-Claude Dubois. The author and Thorbjörn Laike designed the questionnaire. The author collected and analysed the data, and wrote the article.
Paper V:	The author designed and performed the study, and wrote the article. Marie-Claude Dubois critically reviewed the Introduction and Method sections.
Paper VI:	The author designed and performed the study, and wrote the article.

Other publications by the author in the field of daylighting

Bournas I (2020). Daylight in Swedish multi-dwelling buildings: Research on the effects of urban densification, building typology and occupant behavior, Bostadsdagen - Form Design Center, Malmö, 4 February 2020. https://www.chalmers.se/SiteCollectionDocuments/Centrum/CBA/Nyheter/2020/LTH4-Iason_Bournas.pdf

Ferreira T, Bournas I, Dubois M-C (2019). Effect of atrium geometry and reflectance on daylighting in adjacent rooms. Journal of Physics: Conference Series, Volume 1343, 012161. DOI: https://doi.org/10.1088/1742-6596/1343/1/012167.

Bournas I (2018) Introduction to daylight simulation. Book Chapter (12) from Daylighting and lighting under a Nordic sky. Dubois M-C, Gentile N, Laike T, Bournas I, Alenius M. First edition. ISBN: 9789144125770, Studentlitteratur AB, 2019.

Rogers P., Dubois M-C., Tillberg M., Österbring M., Alenius M., Bournas I., Larsson A., Lundgren M., Söderlund M., Vakouli V., Moderniserad dagsljusstandard (English: Modernized daylight standard), SBUF ID: 13209, http://www.bau.se/wp-content/uploads/2018/12/SBUF-13209-Slutrapport-Moderniserad-dagsljusstandard.pdf, 2018.

Bournas I (2017). Workflow for generation of multiple illuminance files for distinct daylit spaces in apartment blocks. IBPSA Nordic, Lund, Sweden, 21-22 September 2017. https://ibpsa-nordic.org/onewebmedia/8.20%20Iason_Bournas_Workflow_for_generation_of_multiple_illuminance_files_.pdf

Bournas I, Haav L (2017). Multi-Objective Optimization of Fenestration Design in Residential Spaces – The Case of MKB Greenhouse. IBPSA Nordic, Lund, Sweden, 21-22 September 2017. https://ibpsa-nordic.org/onewebmedia/8.40%20Iason_Bournas_Multi_Objective_Optimization_.pdf

Dubois M-C, Angeraini S J, Bournas I, Haav L, Levin T, Shalaby M (2017) Innovative solutions for good daylighting and low energy use in multi-family dwellings: MKB Greenhouse, Malmö. E2B2 Report 2017:10. https://www.e2b2.se/library/3529/slutrapport_dagsljuskrav_i_miljocertifierade_byggnader-laengre-version.pdf

Bournas I., Lundgren M., Alenius M., Dubois M-C, Urban densification affects daylighting: existing daylight levels in Swedish multi-family housing as a base for future daylight requirement, Changing Cities III Comf., Syros, GR. 26-30 June 2017, pp. 987-997.

Bournas I., Abugabbara M., Balcerzak A., Dubois M-C., Javed S., Energy renovation of an office building using a holistic design approach, Journal of Building Engineering 7 (2016) 194-206.

Haav L, Bournas I, Angeraini S J (2016). Bi-objective optimization of fenestration using an evolutionary algorithm approach. PLEA Conf., Los Angeles, USA, 11-13 July 2016.

1 Introduction

Sweden's population has grown by a million inhabitants in the past decade (SCB, 2020e), and is still increasing despite a recent drop in immigration and a high number of deaths due to the coronavirus pandemic (SCB, 2020d). As population continues to grow, the distribution of inhabitants is clearly not uniform across the country, with significant regional differences indicating an urbanisation trend. According to the official statistics agency SCB (SCB, 2020f), the urbanised land is unevenly distributed across regions, with the three metropolitan counties (Stockholm, Västra Götaland and Skåne) having the highest percentage of developed urban areas (SCB, 2019d). This clear urbanisation trend (SCB, 2019e) resulted in 87 % of Sweden's population living in urban areas at the end of 2018 (SCB, 2019f). In 2019, the majority of urban areas noted population increases (SCB, 2020c).

This steady population growth partly dictated the building development process, leading to the expansion or densification of urban areas to provide cities with the necessary amount of residential building stock. In February 2016, the Swedish National Board of Housing, Building and Planning (BOVERKET, 2020e), which issues building regulations and supervises municipal and county planning, estimated that roughly 700,000 new dwellings would need to be built by 2025 (OMNI, 2016) to meet the needs of the housing crisis. The construction rate required to achieve such a number of dwellings compares to the historic rate that occurred during the famous Million Homes Programme (Hall and Vidén, 2005), when approximately one million dwellings were built between 1965 and 1974. Although densifying cities offers advantages (e.g. for the transportation sector), there are certain environmental considerations, for instance, access to daylight and sunlight, noise, access to outdoor green spaces, and the need for heavier infrastructures (bridges, subways, etc.), which rely on climate-expensive concrete and steel infrastructures.

To satisfy the housing demand as well as secure their investments, developers have mainly targeted multi-dwelling buildings, i.e. buildings with three or more apartments. This type of building is the most common type in Sweden (51 % of dwellings (SCB, 2019c)), and the most common for new construction since 1985 (SCB, 2019b). It is also the study object of this research. Regarding regulations pertaining to multi-dwelling buildings, the government initiated a comprehensive review of the building code in 2017 in an effort to facilitate the construction process. The aim was to re-formulate certain sections "to modernize the regulations and thereby promote increased competition and increased housing construction" (Regeringskansliet, 2019). This review was assigned to the Building Rules Modernisation Committee (KFMB, 2019b), which submitted its proposal to the government in December 2019 (KFMB, 2019a). Among different amendments to the building code, the committee proposed several "simplifications" to ease the task for developers. For instance, they proposed the exclusion of kitchens from daylight evaluations.

At the same time, concern was raised regarding the impact of densifying urban areas on daylight availability for residential spaces (Bournas and Dubois, 2019; Eriksson et al., 2019; Rogers et al., 2018). Researchers expressed the necessity to shift from the old Swedish daylight criterion that was effectively formulated in 1975 (Bournas, 2021) and is based on a daylight factor assessment, to more sophisticated daylight criteria aligned with international standards and practices. Building developers voiced concerns about the economic feasibility of their projects when daylight criteria must be met in new constructions (SBUF, 2017). Policy makers are today faced with the need to safeguard daylight access for new residential developments, and at the same time, facilitate construction work to mitigate the pressing housing crisis. To achieve this, they require suitable daylight performance criteria.

Daylight provision for buildings has been an integral part of architectural practice since ancient times, yet for the vast majority of countries, daylight criteria were not normative until the 20th century. Formulating normative criteria has proved to be a difficult task, due to the intrinsic variability of daylight, and due to what has been a limited range of simulation models and trained daylight practitioners in the past. Currently there is a multitude of sophisticated tools that can be used to assess spaces, and architectural and consultancy practices have reached an adequate level of competency, at least in terms of daylight evaluations for compliance testing. However, the scientific community has been divided regarding the appropriate method to assess whether a given space is compliant or not (Tregenza and Mardaljevic, 2018). One part of the research community supports the use of daylight factors (Jacobs, 2014; Tregenza, 2014) while another part supports the use of climate-based criteria (Mardaljevic, 2013; Mardaljevic, 2015; Mardaljevic and Christoffersen, 2017; Reinhart et al., 2006). Daylight factors are calculated under a standard sky brightness pattern, the CIE Standard Overcast Sky model (CIE, 2004), a type of sky that rarely occurs in reality, but whose use for compliance testing can be justified since it represents worst-case conditions. Climate-based criteria consider whole-year daylight conditions derived from meteorological datasets, where the sky brightness pattern changes each hour of the year, depending on location and sky conditions (e.g. sun position and irradiation or cloudiness per hour of the year).

Regardless of method or technical requirements, a standard threshold for daylight compliance also depends on economic feasibility. For instance, developers in Sweden have expressed the limitations associated with daylight regulations, voicing the need to build cost-efficiently, (e.g. to maximise the amount of apartments in a given plot or to maximise the depth of an apartment in a given building plan). As expressed by Tregenza and Wilson: "daylighting requirements are effectively constraints on the form and size of buildings and therefore limits on the profitability of an investment" (Tregenza and Wilson, 2011). The financial pressure on policy may be the reason why the Building Rules Modernisation Committee eventually proposed the exclusion of kitchens from daylight evaluations. This comes as a surprise to the author, as there is research (including this one) that Swedes prefer to have more daylight in the kitchen than in any other room (Bournas, 2020b; Eriksson et al., 2019), and other countries have previously regulated higher thresholds for kitchens (e.g. United Kingdom). The financial pressure by developers can be considered productive, as it aims to satisfy the high demand for housing in Sweden, but it is not based on scientific evidence pertaining to occupant biological and psychological needs and preferences.

A suitable daylight criterion should translate to (at least) a minimum illumination level, while not hindering the construction process with unreasonable targets. Different criteria may be "easier" or "harder" to comply with, depending on illuminance thresholds or analysis areas embedded in their formulations (Bournas, 2020a). A criterion that is difficult to meet runs the risk of being abandoned by practitioners, especially if it is not a mandatory one. On the other hand, a criterion that is easy to comply with may not ensure adequate illuminance levels. In reality, different criteria may yield different results in terms of compliance, and may take different parameters into consideration, e.g. façade orientation, glazing area, building type, and room geometry. This thesis was designed to evaluate the importance of such parameters, and to investigate the implications of using different daylight criteria to assess multi-dwelling buildings. In addition, responses obtained from occupants living in such buildings were factored in the analysis, in order to associate apartment characteristics with subjective evaluations of daylight conditions and reports on electric lighting usage.

Aim

This thesis contributes to knowledge supporting the development of more appropriate daylight criteria for residential spaces in the Swedish context. It provides basic information to, e.g., the National Board of Housing, Building and Planning in the development work concerning daylight performance requirements for new constructions.

The aim of this thesis is to provide an overview of the current situation, i.e. the daylight compliance of existing buildings according to current regulations, to assess whether new evaluation criteria are necessary today, and if so, to identify the most important parameters that should be considered in the formulation of new criteria. Different room geometry measures relating to daylight compliance are factored in the analysis. These characteristics are meant to be associated with daylight compliance according to both current and newer, more sophisticated criteria. Occupant responses are meant to strengthen the claim that daylight provision is imperative, to pinpoint the room types that should be prioritised, and to highlight the design parameters that are necessary for residential rooms to be considered adequately daylit.

Research questions

Based on the aim of this thesis, the main research question can be formulated as follows:

- What are the determinants of a suitable daylight criterion for residential spaces?

This leads to the following related questions:

- Are the current evaluation criteria suitable for compliance testing or not?
- What is the effect of urban density on daylight compliance?
- What is the effect of building typology on daylight compliance?
- What is the effect of room geometry on daylight compliance?
- Are there room types on which a daylight criterion should focus more?
- Is there a potential to reduce electric lighting usage with daylight regulation?
- Which factors affect electric lighting usage?

Hypotheses

The main hypotheses are:

- The current daylight evaluation criteria require modernisation due to limitations deriving from the way they are formulated.
- Daylight compliance is primarily dependent on the amount of surrounding obstructions and on the relation between room and aperture size.
- Occupants have clear preferences as to which rooms they prefer to be adequately daylit, and they use less electric lighting when daylight is available.

Limitations

The research scope was limited to multi-dwelling buildings, i.e. buildings with three or more apartments.

The scope was also limited to building block typologies that have been classified as typical in Swedish urban planning practices. However, for the buildings of a given typology, apartment layouts, room geometric characteristics or surroundings are not identical, due to intrinsic variations in architecture and urban planning practices. Buildings of the same typology are similar, but not identical. With the necessary design customisations, architectural practice can produce residential blocks that deviate from the designs studied here.

The apertures identified in the evaluated spaces were limited to vertical windows or glazed doors, i.e. there were no rooms with skylights. The results are thus relevant only for side-lit spaces.

Most of the work was based only on simulations and surveys.

Simulations were conducted using typical optical properties for surface finishes, according to standards and good-practice recommendations, not according to in-situ measurements. Measuring surface reflectances in 45 residential rooms by means of a portable spectrophotometer showed that the typical properties used are reasonable assumptions for dwellings, but occupant preferences may result in surface finishes that are darker than the ones assumed for this work.

Glazing light transmittance was set to 70 % for all simulations, assuming the use of triple-glazed units with clear panes, a low emissivity coating, and argon filling. This can be considered a reasonable glazing setup for housing projects in Sweden. However, real light transmittance values could vary from 62 % for windows with additional coatings (e.g. solar control) to 75 % for uncoated triple-glazed units or coated double-glazed units.

The questionnaires used in this thesis were sent via normal mail, randomly, and in strata of different building typologies. As participation was voluntary, the response rate per building typology could not be controlled. Using self-administered questionnaires also meant that respondents could not ask questions regarding questionnaire items, and that non-response could not be controlled.

The questionnaires were sent around the time of the Spring Equinox in 2018, in order for the survey to occur during "average" conditions with respect to daytime duration. However, the exact point in time when each occupant gave their responses could not be controlled. This effectively resulted in the sky conditions differing between respondents, which limits the analysis of the association between room geometry and occupant responses on room brightness due to the confounding role of solar irradiation.

The questionnaire was not designed to include specific instructions regarding positioning in space or view direction for respondents. This could affect results pertaining to the association of occupant responses with geometric attributes. For instance, one occupant standing in the doorway to the room staring towards the window and another occupant standing with their back against a window of equal size but staring towards the room door could report different daylight conditions for the same window.

Thesis structure

This is an article-compilation thesis, consisting of six articles (Papers I-VI).

Section 2 provides a review of Swedish daylight regulations, from when the term "daylight" first appeared in building regulations, 60 years ago. This section is also included in Paper I, section 2.

Section 3 includes the general methods used. Section 3.1 provides background information regarding the selected multi-dwelling buildings. Section 3.2 provides information regarding the daylight simulations used. Section 3.3 provides information on the structure of the questionnaire used.

Section 4 provides a summary of the appended articles.

Section 5 discusses the implications of the thesis findings on the formulation of daylight evaluation criteria.

The final sections include the conclusions drawn (Section 6) and future work that could depart from where this research stopped (Section 7).

2 Review of daylight regulation in Sweden

The reader may find this section as part of the first appended article (Paper I, section 2).

2.1 Overview

The daylight regulatory framework for Swedish residential spaces was initially developed as a counter-policy to the energy regulations following the 1970 oil crisis. Since windows constitute the weakest thermal barrier of the building envelope, energy regulations of that time effectively constrained fenestration sizes as a means to reduce the heating demand. This deemed daylight design rules necessary to prevent large reductions of fenestration, to safeguard natural illumination. The following paragraphs describe the evolution of daylight criteria in Swedish building codes over time. Figure 2.1 illustrates when different criteria came into force.

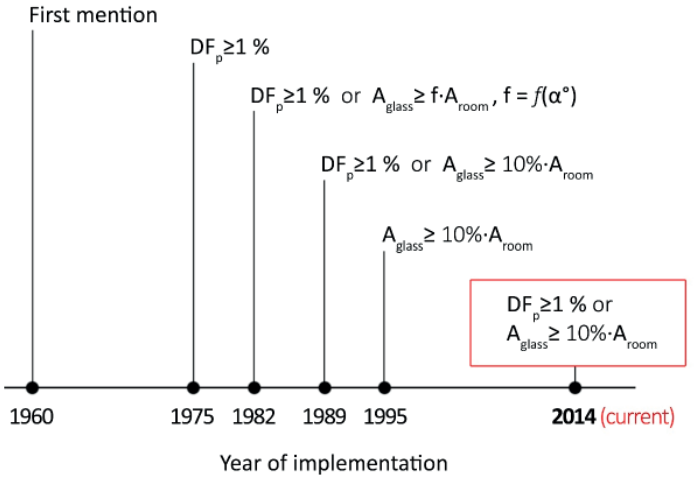


Figure 2.1 *Evolution of Swedish daylight criteria for residential spaces. DF_P: Point Daylight Factor as defined in Swedish regulations, A_{glass}: Room glazing area, A_{floor}: Room floor area, α°: Glazing obstruction angle, as defined in Swedish regulations.*

2.2 Type of criteria

Daylight admission for room interiors has always been a goal of architectural practice, even though it was not explicitly stipulated by formal policy until the 20th century. Relevant literature (Boubekri, 2008; Julian, 1998) suggests that daylight legislation has been historically based on either one of the following: i) access to sunlight (solar zoning), ii) window size, and iii) quantity of illumination. The first type of legislation stipulates that particular parts of buildings should have access to direct sunlight for an adequate length of time. The second type, which is most often found in building codes (Kunkel et al., 2015), requires that rooms are equipped with sufficiently large window openings, the window area used as a proxy of actual indoor illumination. The third type, which is currently making its way to international standards, certification systems and national building codes, relates to minimum indoor illuminance levels, i.e. it refers to measurements (or predictions) of illuminance. During the course of the 20th century, Sweden has formally stipulated daylight criteria of the second and third type.

Swedish building codes did not account for daylight provision until 1975, yet there were eras prior to that when residential rooms were provided with large fenestration areas and sufficient spacing between buildings. This indicates that there was an intention to provide natural illumination prior to the introduction of explicit daylight criteria. However, despite their introduction, quantified daylight criteria in Sweden were always stated as "general recommendations". General recommendations are lower in the Swedish regulatory hierarchy, and are not legally binding (BOVERKET, 2020d). They state what "can be done" to meet "mandatory provisions", which in turn are qualitative. For instance, the current mandatory provision pertaining to daylight states: "rooms or separable parts of rooms where people are present other than occasionally shall be designed and oriented to ensure adequate access to direct daylight is possible, if this does not compromise the room's intended use" (BOVERKET, 2020b). To achieve this, the general recommendation given is either to ensure a minimum glass-to-floor ratio of 10 % (GFR-method criterion) or to meet a daylight factor threshold of 1 % measured on a specific point in the room (DF_P criterion). The GFR-method is only applicable when certain room geometric conditions are met. When these conditions cannot be met, the DF_P assessment method should be used.

2.3 First mention of "daylight"

The term "daylight" was first mentioned in building regulations in code BABS 1960 (KBS, 1960), which constituted "an attempt to obtain uniform regulations across Sweden, as opposed to previous local regulations" (BOVERKET, 2020a). Under section 57:2, "General facilities of staff rooms" and in subsection 57:26 "Window", the following is stated: "Dining rooms should have windows to the outside, which, unless otherwise used by the ventilation system, should be openable. Even in changing rooms and laundry rooms, daylight should be sought." However, this statement cannot be regarded as a strong intent to ensure daylight availability. It was more an intent to ensure hygiene in utility rooms (laundry rooms, drying rooms, toilet rooms, etc.). Reading through the rest of the section reveals that hygiene is the dominating factor of design instructions: "Staff rooms should be so arranged and furnished that personal hygiene is promoted". Daylight provision for main rooms, i.e. living rooms, bedrooms, and kitchens, was considered self-understood for architects of that era. There was therefore no imperative need to define daylight design rules yet, not until the next decade.

The subsequent building code SBN-67 (SP, 1967) that came into force in 1968 included no mention of the term “daylight”. The National Board of Housing, Building and Planning (BOVERKET, (BOVERKET, 2020c)), which issues building regulations today, describes the main aim of this code as “to design the regulations as functional requirements and to coordinate all regulations relating to house construction” (BOVERKET, 2020a). The absence of reference to daylight can be attributed to the fact that this code included more details with respect to ventilation hygienic flows for utility rooms, which effectively meant that windows for air intake were not an absolute necessity anymore. Relevant literature suggests that this code indeed prioritised building services and technical solutions for hygiene (Rogers et al., 2018). Unfortunately, the timespan between 1961 and 1975, which included either a qualitative mention for utility rooms (1961-1968) or no mention (1968-1975), was a period of urbanisation and rapidly growing demand for housing. It was characterised by historically high rates of new residential constructions (“Record Years”), and the famous Million Homes Programme (Hall and Vidén, 2005).

2.4 Energy crisis and the formulation of quantified daylight criteria

The first formulation of a numerical (i.e. quantified) daylight criterion appeared in 1975, with code SBN-75 (SP, 1975). In Chapter 38, section 38:1, it was stated that daylight was considered acceptable “if a daylight factor of 1 % is achieved for a point located halfway through the room depth, one meter from the darkest lateral wall, 0.8 m above floor level” ($DF_P \geq 1$ %). Figure 2.2a shows the location of the DF_P point in a room. The criterion was set for “residential rooms, such as living rooms, bedrooms, and kitchens, as well as children’s playrooms.” Another section referring to thermal insulation (section 33:2) stated: “the window area is determined with regard to the requirement for good energy use, however taking into account the requirements for daylight in Chapter 38.” The latter confirms that daylight was initially regulated to avoid dramatic reductions of fenestration to meet energy requirements. These regulations notwithstanding, Marsh (2017) refers to the decade following the oil crisis (1975-1985) as the “fabric heat-loss paradigm” in Scandinavian regulations, and argues that this paradigm resulted in low indoor daylight levels. Sweden in particular subsidised energy saving measures in the residential sector on a large scale between 1974 and 1983 (Legnér et al., 2020). Considering the focus on reducing space heating, it can be inferred that inserting a quantified daylight criterion at that time was a wise choice, but it would have been wiser if it were a “mandatory provision” instead of a “general recommendation”.

According to SBN-75, practitioners were instructed to calculate DFP as per the method provided by Fritzell and Löfberg (1970), which involved the use of a daylight protractor (Dufton, 1946). Due to the complexity associated with this type of calculation, the subsequent code SBN 1980 (SP, 1980b) introduced an alternative method to predict daylight availability based on the room glass-to-floor ratio (GFR-method). This method was described in Chapter 38:1K of a complementary report “Kommentarer till Svensk Byggnorm” (English: Comments on Swedish Building Code (SP, 1980a)), which included clarifications to SBN-80. It assumed that this minimum window glazing area has a commensurate effect on illumination as a DFP ≥ 1 %. The method stipulated that the minimum glazing area should be equal to the product of the room floor area and a factor f ranging between 0.07 and 0.13 ($A_{glass} \geq f \cdot A_{room}$) depending on the window obstruction angle $\alpha°$ (see Figure 2.2c for the definition of obstruction angle). This assessment method effectively stipulated minimum glazing areas between 7 % and 13 % of the room floor area, depending on surroundings. If a balcony obstructed the façade, the considered room floor area would have to include the balcony area adjacent to the façade. The method was applicable only under specific conditions pertaining to room depth, width and height, and glazing width and height (Figure 2.2 b, c ,d). In addition, it was not valid for obstruction angles higher than 30°. For rooms violating these conditions, the DFP method was to be used instead, aiming for a DFP ≥ 1 %, calculated using a daylight protractor according to the method described by Fritzell and Löfberg (1970).

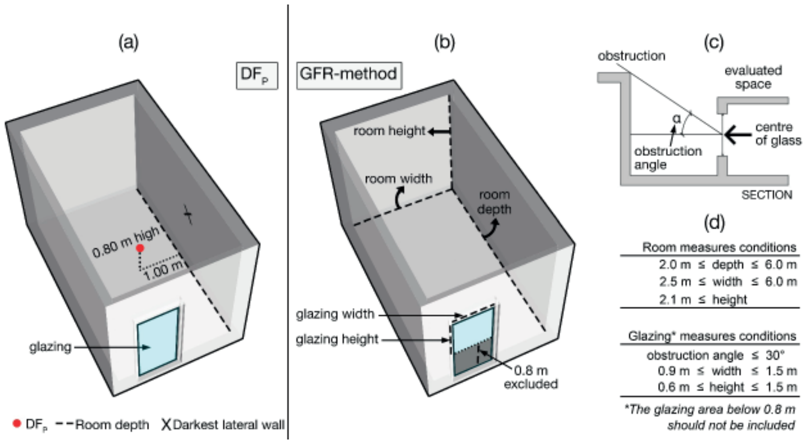


Figure 2.2 *a) Location of the calculation point (red point) for the DF$_P$ assessment, b) room and glazing measures relevant to the GFR-method assessment, c) the obstruction angle measure and d) the geometry conditions for the applicability of the GFR-method.*

2.5 Simplification of criteria and deregulation

In the years following 1982, energy regulations progressed, demanding ever-lower heating requirements for residences, while daylight criteria lagged behind. In 1989, code BFS 1988:18 (BOVERKET, 1988) simplified the GFR-method calculation by replacing factor f with a constant, i.e. it removed the sensitivity to surrounding obstructions. The new code simply stipulated that the glazing area would have to be no less than 10 % of the room floor area ($A_{glass} \geq 10\ \% \cdot A_{room}$), a glass-to-floor ratio commonly used in national codes (Kunkel et al., 2015). The code included a note that "in cases of obstruction angles higher than 20°, the glazing area should be increased", but it did not specify the magnitude of this increase.

This simplified GFR-method was regulated at a time when Stockholm made a crucial transition in urban planning: the shift from expansion to densification (Hall and Rörby, 2009). In essence, planning tendencies focused more on central areas, using high building volumes to satisfy housing demands. Urban density and self-shading of buildings resulted in a higher amount of dim rooms, as is shown in this research. As before, if a room violated any geometry condition (Figure 2.2 d), practitioners would have to calculate DFp according to standard SS914201 (SIS, 1988). The DFp calculation method was the one introduced in 1975 (using daylight protractors), and it seemingly found little acceptance among practitioners. From 1995 (BOVERKET, 1993) until 2014 (BOVERKET, 2014), the quantified DFp ≥ 1 % criterion was completely removed from building codes, which only included the simple GFR-method ($A_{glass} \geq 10\ \% \cdot A_{room}$). A reasonable explanation is that the DFp calculation was too complicated to be adopted on a large scale, compared to a simple geometry calculation. Effectively, the $A_{glass} \geq 10\ \% \cdot A_{room}$ was the only devised daylight criterion until 2014, not applicable unless geometric conditions were met, and legally set as a general recommendation.

2.6 Revival of DFp criterion and current state

When code BFS 2014:3 (BOVERKET, 2014) came into force, the DFp ≥ 1 % criterion was reinstated, as advances in computation made it easier for practitioners to calculate accurate DFp values by means of simulation software instead of daylight protractors. Simulation tools validated for agreement with full-scale spaces were now readily available and compatible with CAD software already adopted by the industry. Soon after its revival, an increased interest was expressed towards modernising the DFp criterion (Rogers et al., 2018). On the other hand, building developers voiced their concerns regarding potential design constraints stemming from daylight requirements, threatening the profitability of their investments. To this end, researchers suggest that a suitable criterion for large-scale application needs to satisfy both technical and economic aspects (Tregenza and Mardaljevic, 2018; Tregenza and Wilson, 2011). The current situation in Sweden points towards some degree of compromise between the two. It seems that the technical aspects will be satisfied by adopting a method closer to European Standard EN-17037 (CEN, 2018b), which is considered by BOVERKET as being superior to the DFp calculation method. As for the financial aspect, it seems it will be satisfied by excluding some spaces from evaluations, in particular the kitchen space, as recently proposed by the Building Rules Modernization Committee (KFMB, 2019b). The latter was appointed in 2017 to conduct a systematic review on the application of the European construction standards and the standards they refer to in order to “modernize the regulations and thereby promote increased competition and increased housing construction without compromising health, safety, quality of design, a good living environment and long-term sustainable construction” (Regeringskansliet, 2019).

3 General methods

The aim of this thesis is to contribute with knowledge supporting the development of daylight criteria that are suitable for residential spaces. Figure 3.1 illustrates the overall methodological scheme followed. Focusing on the built environment, two factors affecting daylight availability in urban areas were considered: geometry (of buildings and rooms) and urban density (of the built environment surrounding the analysed buildings). In order to derive information that can be useful for devising daylight regulations (basis for daylight evaluation criteria), two research methods were combined: simulation and survey. The two methods were applied in two building samples of different locations (simulation: Stockholm, survey: Malmö) and different sizes, i.e. a different amount of rooms was evaluated per method. The survey involved significantly fewer rooms (n = 225) due to practical issues associated with surveying occupants living in real apartments compared to simulating daylight levels in computer-generated geometric models (n = 10888).

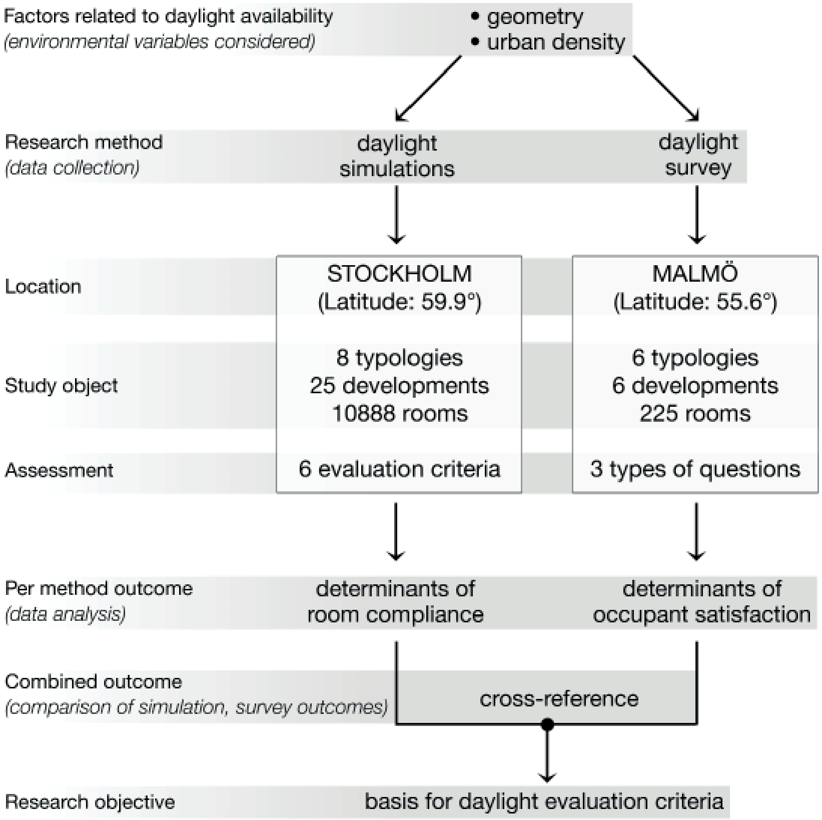


Figure 3.1 Schematic representation of the thesis workflow.

The simulation part assessed the relation between variables of geometry and urban density on one hand, and compliance with daylight criteria on the other. The analysis of the simulation results focused on identifying the variables that are more strongly associated with compliance, i.e. the determinants of daylight compliance. The survey part assessed the relation between variables of geometry and urban density on one hand, and occupant responses regarding daylight conditions and electric lighting use on the other. The analysis of the data focused on identifying the variables that affect occupant perception of daylight conditions and electric lighting use. Finally, the findings of the two research methods were collated to derive information regarding which variables and consequently which daylight criteria could be used in daylight regulations pertaining to multi-dwelling buildings.

The following sections provide background information regarding the methods used. Section 3.1 provides general descriptions of multi-dwelling building types relevant to this thesis and geometry data regarding the specific developments that were analysed. Section 3.2 provides information regarding the daylight simulations used. Section 3.3 provides information regarding the survey and the questionnaire used.

3.1 Multi-dwelling buildings

The study object of this thesis is the multi-dwelling building, which is defined as a building comprising at least three apartments. In Sweden, these buildings currently represent 51 % of the residential building stock (SCB, 2019a), and for the past decade, they have dominated the market for new constructions (Figure 3.2). This thesis evaluated existing residential developments located in urban areas, i.e. areas that have contiguous buildings with no more than 200 m between houses (SCB, 2020a). An important selection criterion was the type of building form and its repetition across the plot, which forms a residential urban block. Depending on the type of building form, a residential block may consist of one or more buildings. Typically, the area covered by a block is in the order of 1-3 hectares.

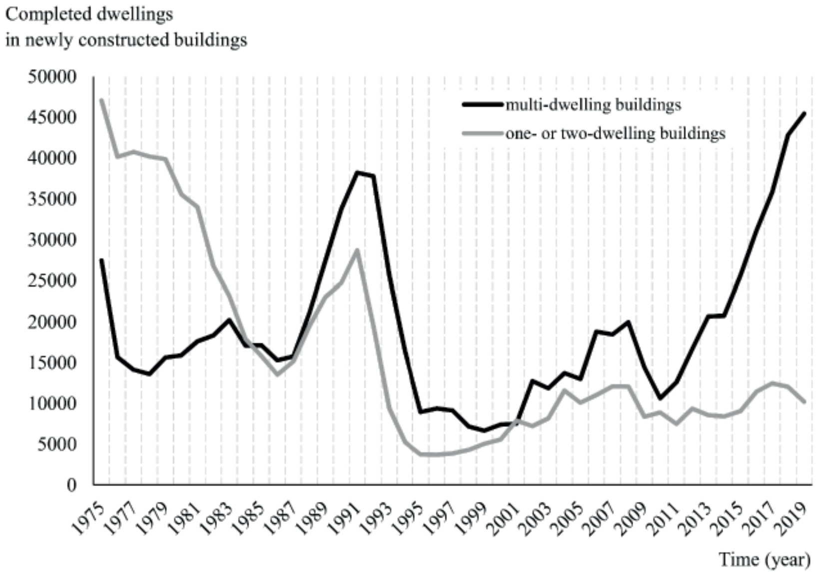


Figure 3.2 *Completed dwellings in newly constructed buildings by type of building and year. Data retrieved from Statistics Sweden (SCB, 2019b).*

3.1.1 Selection criteria

Swedish literature has documented typical multi-dwelling buildings (Swedish: *flerbostadshus*) that can be identified in the current building stock. The typical building classification is based on the combination of architectural design and construction characteristics. Elements such as building length, width, or number of storeys, together with construction systems or facade materials, define examples of typical residential buildings of different eras. A categorisation of building types based on prevailing architectural styles and construction systems by decade can be found in Björk et al. (Björk et al., 2013). However, for the purpose of this research, a typology that incorporates an urban planning perspective was judged as more appropriate, in order to assess daylight performance at the neighbourhood scale, and to account for built space density around the evaluated developments. In this sense, a classification of "urban types" seemed more useful than a classification of "building types".

A systematic categorisation of residential developments in "urban types" (in Swedish: *stadstyper*) was made by Rådberg and Friberg (1996). This categorisation follows an urban typo-morphological approach, where the overall neighbourhood is taken into account. According to Rådberg and Friberg (1996), the main elements of urban typo-morphological studies are: 1) the street network, 2) the property subdivision, and 3) the buildings and courtyards (i.e. the buildings related to the open space). The spatial description of an urban type therefore focuses on the neighbourhood, and can consider both the individual building type and the urban pattern created by repeating buildings across the neighbourhood area. This is particularly relevant to this thesis, as the study object is residential spaces, which are normally developed using recurring elements with a set of design rules (e.g. building heights, distances between buildings, building blocks orientation, and courtyard formations).

Rådberg and Friberg (1996) identified 26 Swedish urban types of dwellings during the period between the pre-industrial era and the turn of the 21st century. They also argued that there is consistency between type and corresponding built density, the density quantified with the plot ratio (the ratio of total floor area to site area). For this thesis, eight of these urban types were selected. The selection criteria were the following:

- A diverse set of urban types, i.e. include buildings with different forms and heights
- Urban types that yield a higher buildable area for a given plot, i.e. a higher plot ratio

- Urban types that include buildings with different plan organisations (apartment units per stairwell)
- Urban types constructed in different decades between 1920 and 2000, with a sampling according to the actual construction rate during each decade.

For the remainder of this thesis, the eight selected “urban types” are called “typologies”. The general characteristics of each typology are provided in section 3.1.2. Detailed characteristics of the developments selected specifically for this thesis are provided in section 3.1.3.

3.1.2 General characteristics of typologies

Low-rise towers (Swedish: låga punkthus)

Groups of low-rise towers are also known as groups of low-rise “point houses”, a term deriving from the building’s concentrated plan. According to Rådberg and Friberg (1996), low-rise towers were traditionally built along the street axis during the 1930s and 1940s (similarly to Figure 3.3c), and were used in hilly terrain during the post-war period, since elongated building shapes are more difficult to place in steep slopes. During the 1960s and 1970s, closely spaced low-rise towers could occupy extensive areas in the suburbs. When repeated to form a larger-scale development, such building volumes do not provide a clear demarcation between the public and private space. The buildings are usually three to four storeys high and elevator-free. Their plan comprises three or four apartment units around a central stairwell, and the apartments usually have double-aspect rooms in the corners (as in Figure 3.3b), most often living rooms. A disadvantage of low-rise towers compared to other typologies is the low plot ratio, i.e. they can only provide a low number of apartments for a given plot area.

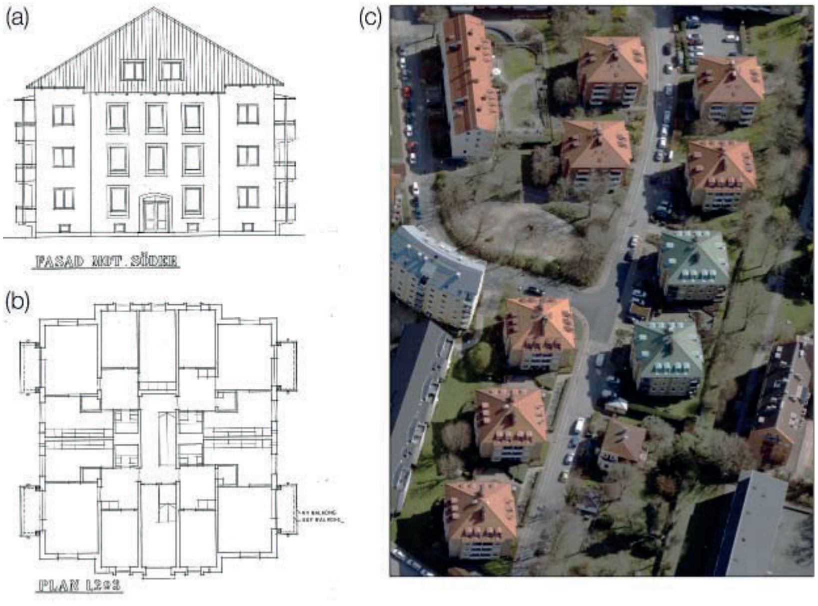


Figure 3.3 *a) South façade, b) typical floor plan, and c) aerial view of a "low-rise towers" development. This development was selected to represent this typology in the survey study. Figures 3.3a & 3.3b were retrieved from the municipal drawing archive of Malmö (Malmö-Stad, 2020b). Figure 3.3c was retrieved from the municipal web application Malmö Stadsatlas (in English: Malmö City Map) (Malmö-Stad, 2020a).*

High-rise towers (Swedish: höga punkthusgrupper)

High-rise towers have a plan similar to that of low-rise towers, except they always have one or two elevators due to their height, up to 16 storeys (Rådberg and Friberg, 1996). Their use in construction started around 1940. They were built mainly in suburbs to increase density while providing adequate daylight and ventilation for dwellings. Some areas were built using high-rise towers exclusively, such as the dominant Danviken cliffs in Stockholm, designed by Sven Backström and Leif Reinius, included in this thesis. The plan of high-rise towers consisted of three or more apartment units, depending on apartment size. In cases of towers with squared plans, one floor could accommodate four double-aspect apartment units (one in each corner), with circulation areas placed in the core of the building. In cases of slightly elongated towers, the plan could accommodate four double-aspect apartment units in the corners and one or more single-aspect units (usually smaller ones) across the longer facades (as in the plan shown in Figure 3.4b). When prefabricated elements became more common, high-rise towers were replaced by elongated building blocks, a typology described further down.

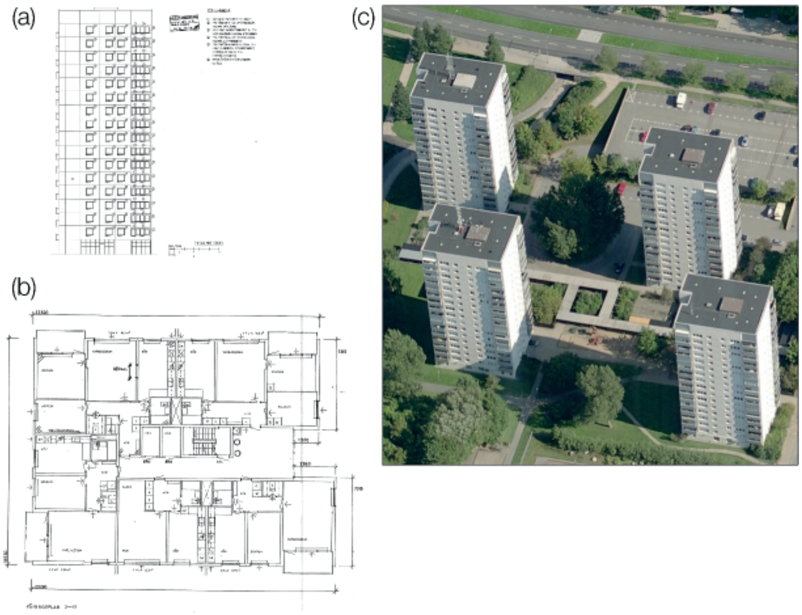


Figure 3.4 *a) South façade, b) typical floor plan, and c) aerial view of a "high-rise towers" development. This development was selected to represent this typology in the survey study. Figures 3.4a & 3.4b were retrieved from the municipal drawing archives of Malmö (Malmö-Stad, 2020b). Figure 3.4c was retrieved from the municipal web application Malmö Stadsatlas (in English: Malmö City Map) (Malmö-Stad, 2020a).*

High + Low combination (Swedish: kombinationer av höghus och låghus)

This typology combines high-rise and low-rise buildings. It was used during the 1950s and after the introduction of prefabricated elements in the 1960s (Rådberg and Friberg, 1996). The intention was to utilise the advantages of both types in a single development. The low part, usually an elongated building, provided sufficient ventilation and daylight for most rooms due to its limited width, but was costly in terms of apartment units per stairwell (normally two units per stairwell). The high part provided a high number of units and a dramatic elevation profile that was distinguishable from a distance. In some cases, the elongated lower part was rotated to form semi-open courtyards as shown in Figure 3.5c.

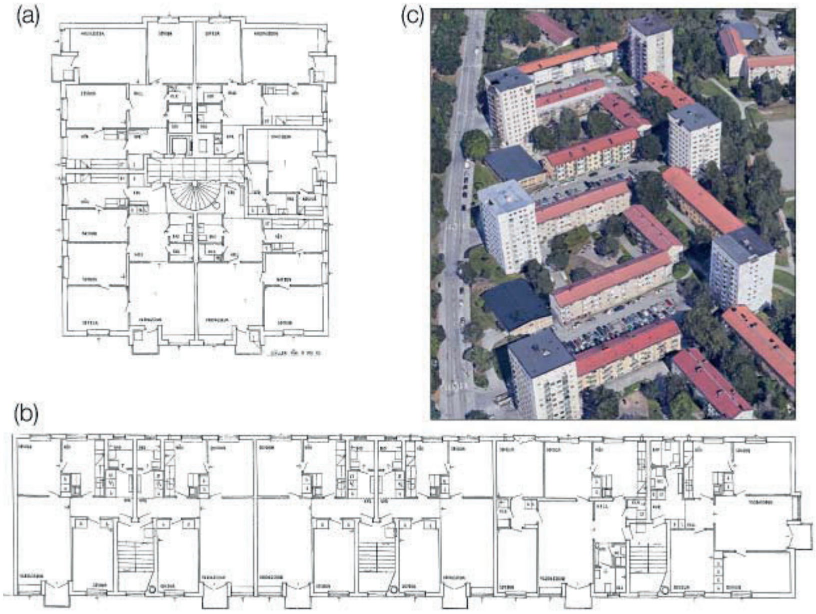


Figure 3.5 *a) Typical floor plan of the high-rise part, b) typical floor plan of the low-rise part, and c) aerial view of a "high + low combination" development. A high and a low building of the depicted development were included in the simulation study. Figures 3.5a & 3.5b were retrieved from the municipal drawing archives of Stockholm ("Stockholm stad, Bygg och plantjänsten (In English: Stockholm city, Construction and planning service)," 2018). Figure 3.5c © Google, Landsat/Copernicus and Data S O, NOAA, U.S. Navy, NGA, GEBCO.*

High-rise elongated (Swedish: skivhusgrupper)

This typology is characterised by freestanding buildings that are at least 50 m long and usually six to ten storeys high, but can reach up to 15 storeys (Rådberg and Friberg, 1996). This type of buildings were used more extensively after 1960, when prefabrication became common, to satisfy the high housing demand of the time. To this end, "high-rise elongated" buildings can be considered successors of "high-rise towers". In many cases, the buildings were oriented in the same direction, surrounded by both parks and parking areas with feeder streets (Björk et al., 2013), similar to Figure 3.6c. Buildings of this typology had typically three to four stairwells. Fire regulations in the 1960s did not require double elevators or specially insulated stairwells for buildings with less than nine storeys, which led to the construction of many such buildings with a height of eight or nine storeys to reduce costs (Länsstyrelsen i Stockholms, 2004). Narrower plans (approximately 10 -12 m wide) could provide two or three apartment units per stairwell, most of them being double-aspect apartments. Wider plans could utilise an internal corridor (as in Figure 3.6b) to provide access to both single and double-aspect units, increasing the number of apartments per stairwell.

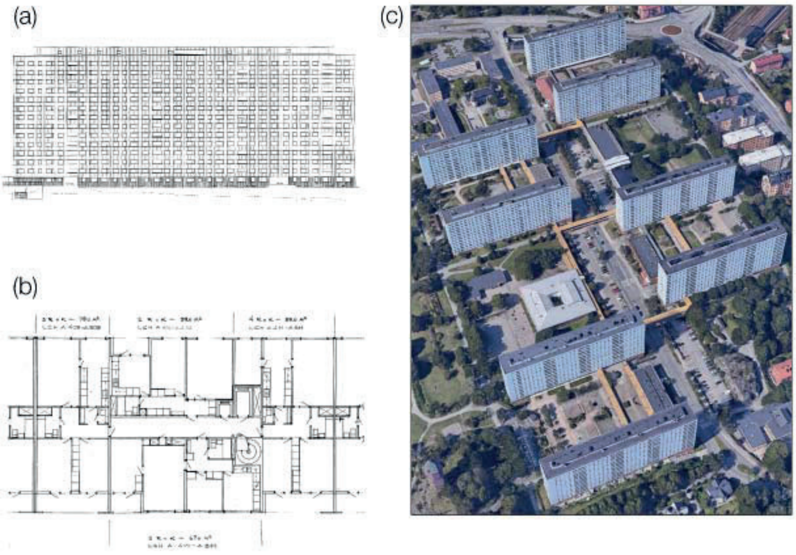


Figure 3.6 *a) West facade, b) typical floor plan per stairwell, and c) aerial view of a "high-rise elongated" development, with a wider plan. One of the depicted buildings was included in the simulation study. Figures 3.6a & 3.6b were retrieved from the municipal drawing archives of Stockholm ("Stockholm stad, Bygg och plantjänsten (In English: Stockholm city, Construction and planning service)," 2018). Figure 3.6c © Google, Landsat/Copernicus.*

Exterior circulation (Swedish: loftgånghus)

The "exterior circulation" typology was mainly used under the Million Homes Programme (Hall and Vidén, 2005) between 1965 and 1974, and is a variation of the "high-rise elongated" typology. The name *loftgånghus* is derived from the long balcony corridor that runs along one façade of the building to provide access to the apartments, similar to the building in Figure 3.7. This design effectively distributes elevator costs to a higher number of apartment units. The long common corridor also satisfied demands for more social interaction between residents, increasing the sense of neighbourhood. These buildings were normally four to six storeys high (Rådberg and Friberg, 1996), with a plan that provided four to eight apartment units per stairwell. Disadvantages of this typology include less privacy and self-shading due to the balcony. A survey of the National Swedish Building Research Institute on attitudes towards "exterior circulation" buildings when they were still new (1971) found that multiple residents perceived their kitchen as being dark due to the balcony corridor (Andersson et al., 1971).

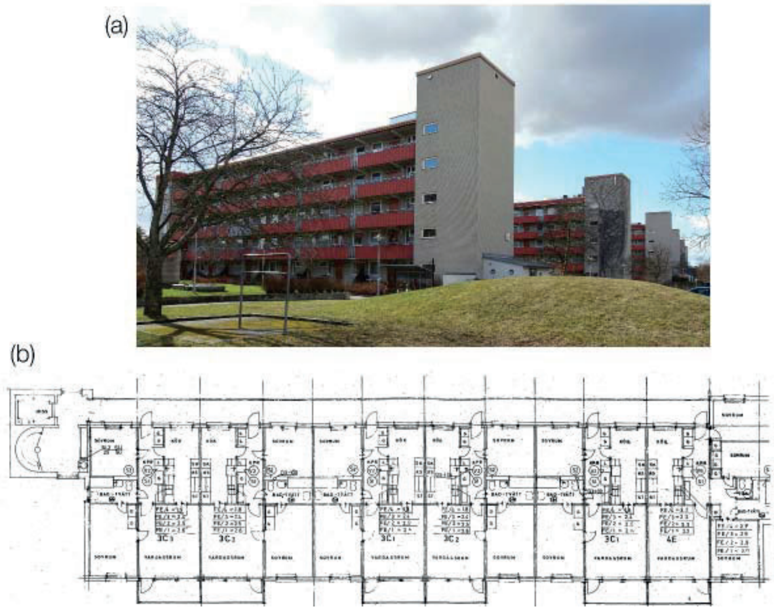


Figure 3.7 *a) Photograph of the long balcony façade and b) typical floor plan of an "exterior circulation" development, with one stairwell providing access to six apartment units. One of the depicted buildings was included in the simulation study. The photograph in Figure 3.7a was taken by architect and photographer Holger Ellgard and is licensed under CC BY-SA 4.0. It was cropped for Figure 3.7a. Figure 3.7b was retrieved from the municipal drawing archives of Stockholm ("Stockholm stad, Bygg och plantjänsten (In English: Stockholm city, Construction and planning service)," 2018).*

Semi-open courtyard (Swedish: halvslutna gårdar)

This typology combines narrow building blocks in larger complexes. The repeated and rotated module is the linear narrow building of the 1930s, arranged in formations that create semi-open, private courtyards. Semi-open courtyards were built primarily in the suburbs, between 1940 and 1960, following functionalistic architecture. The modules were typically low-rise, two to three storeys high (Björk et al., 2013) and their width could be as narrow as 8 m, and not significantly wider than 10 m. According to Rådberg and Friberg (1996), this typology was used more extensively during the 1950s, combining buildings of linear, L-shape or U-shape forms. Hall and Rörby (2009) note that the narrow module provided an advantage with respect to daylight availability and ventilation. On the other hand, the disadvantage of "semi-open courtyard" developments was that the stairwell occupied a high proportion of the building floor area, increasing the building cost. On the plan layout, this meant less apartment units per stairwell, usually two or three double-aspect apartments, as shown in Figure 3.8b.

Figure 3.8 *a) Aerial view and b) typical floor plan for a part of a "semi-open courtyard" development. Multiple parts of this development were included in the simulation study. Notice the narrow building volume (8.9 m wide), with two apartment units per stairwell across the linear part and three units in the part that forms the courtyard corner. Figure 3.8a © Google. Figure 3.8b was retrieved from the municipal drawing archives of Stockholm ("Stockholm stad, Bygg och plantjänsten (In English: Stockholm city, Construction and planning service)," 2018).*

Large courtyard blocks (Swedish: storgårdskvarter)

This way of defining a city block emerged after the 1907 Town Planning Act (SFS, 1931), which effectively banned the previous practice of constructing building rows inside courtyards. Hall and Rörby (2009) suggest that this large, park-like inner courtyard was characteristic of 1920s developments. They also point that "an orthodox large courtyard block should be built by a single contractor and a single architect, to ensure that each block has a cohesive design" (Hall and Rörby, 2009). According to Rådberg and Friberg (1996), large courtyard blocks constituted a reform, as the 1907 Town Planning Act made it possible to prescribe lower building heights and lower plot ratios compared to the general rules of the Building and Fire Charter (BS, 1874), which was the regulatory framework up to that time (effective since 1875). Large courtyard blocks appeared in new cities and inner parts of larger cities. They had a relatively uniform height across the block, usually four or five storeys (Rådberg and Friberg, 1996) similar to the building block in Figure 3.9a. An important factor relating to daylight performance is that these buildings are commonly found in central, densely built areas, which means that the sky is significantly obstructed for room apertures, especially for rooms located in the lower floors.

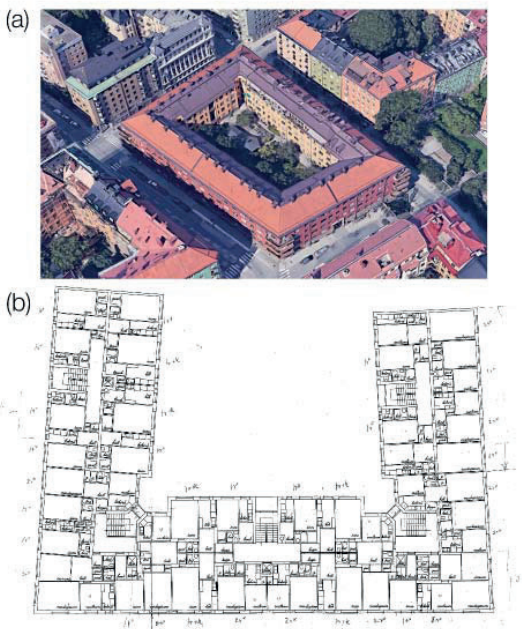


Figure 3.9 *a) Aerial view and b) typical floor plan for a part of a "large courtyard blocks" development. This development was included in the simulation study. Figure 3.9a © Google, Landsat / Copernicus. Figure 3.9b was retrieved from the municipal drawing archives of Stockholm ("Stockholm stad, Bygg och plantjänsten (In English: Stockholm city, Construction and planning service)," 2018).*

Post-modern reforms

According to Hall and Rörby (2009), the transition period between the 1920s and functionalistic architecture (which featured "large courtyard blocks") was a source of inspiration for architects in the 1980s and 1990s. Another influence was post-modernism. After 1975, there was an intent to paraphrase traditional blocks into post-modern blocks, using different arrangements of building volumes and design axes. Although the similarities with the older blocks are striking, Rådberg and Friberg (1996) point that there are principal differences. The "post-modern reforms" developments do not have a uniform height across different parts, and they reach up to eight storeys (the older "large courtyard blocks" reached up to five). The new blocks also have a more blurred limit between the street and the private courtyard, which is manifested by breaching the courtyard volume in specific locations (as in Figure 3.10a).

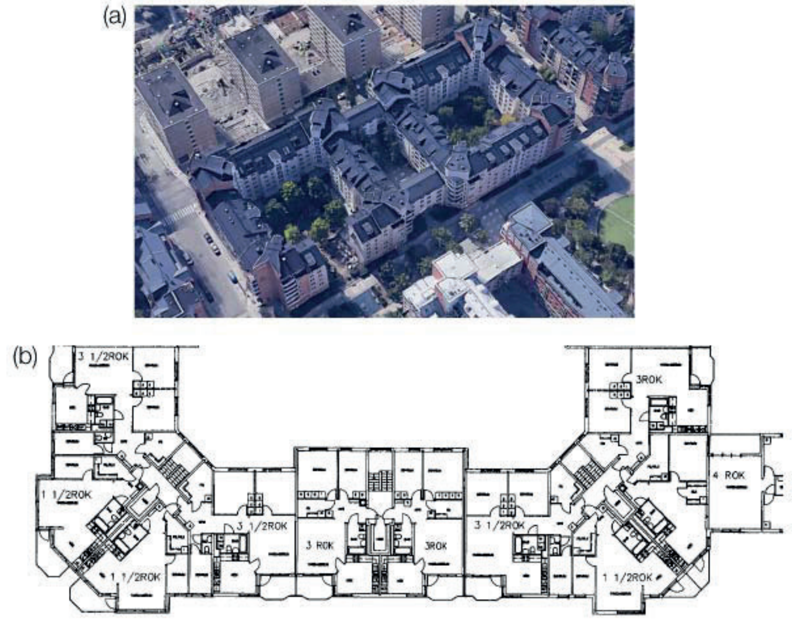


Figure 3.10 *a) Aerial view, and b) typical floor plan for a part of a "post-modern reforms" development. This development was included in the simulation study. Figure 3.10a © Google, Landsat / Copernicus. Figure 3.10b was retrieved from the municipal drawing archives of Stockholm ("Stockholm stad, Bygg och plantjänsten (In English: Stockholm city, Construction and planning service)," 2018).*

3.1.3 Specific characteristics of the selected developments

One part of this thesis performed daylight simulations for multi-dwelling buildings, and the other used self-administered questionnaires to assess responses from occupants of multi-dwelling buildings. The simulation study was performed for 25 developments located in urban areas of the central and metropolitan regions of Stockholm (latitude: 59.93°). Stockholm is the largest city in Sweden and the city with the highest annual addition of dwellings (in multi-dwelling buildings) for at least the past decade (Figure 3.11). To acquire a representative sample, at least three developments were selected per typology. The survey study was performed in six developments, located in urban areas of the central and suburban region of Malmö (latitude: 55.61°). Malmö is the third largest city in Sweden, and a city with a fast-growing dwelling stock housed in multi-dwelling buildings (Figure 3.11).

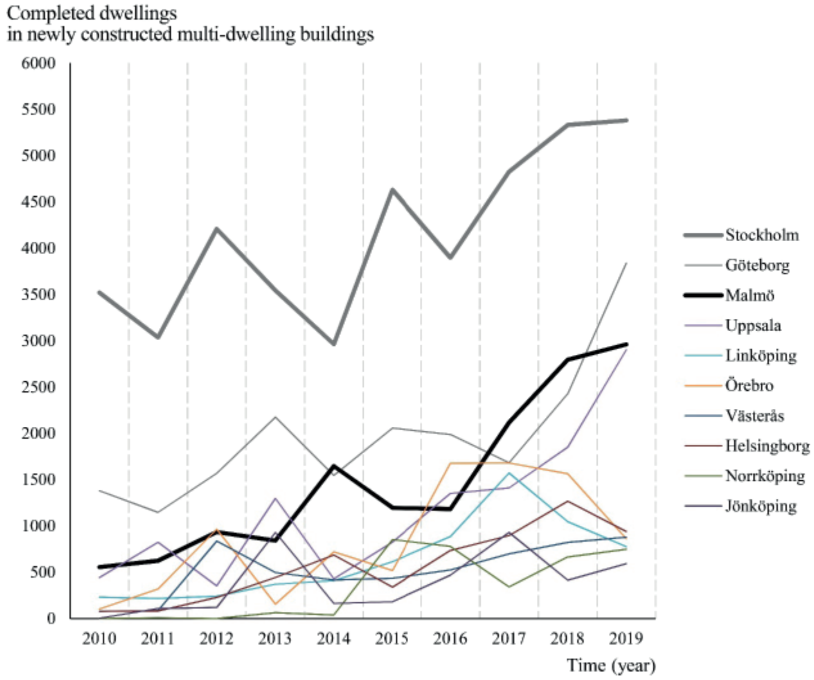
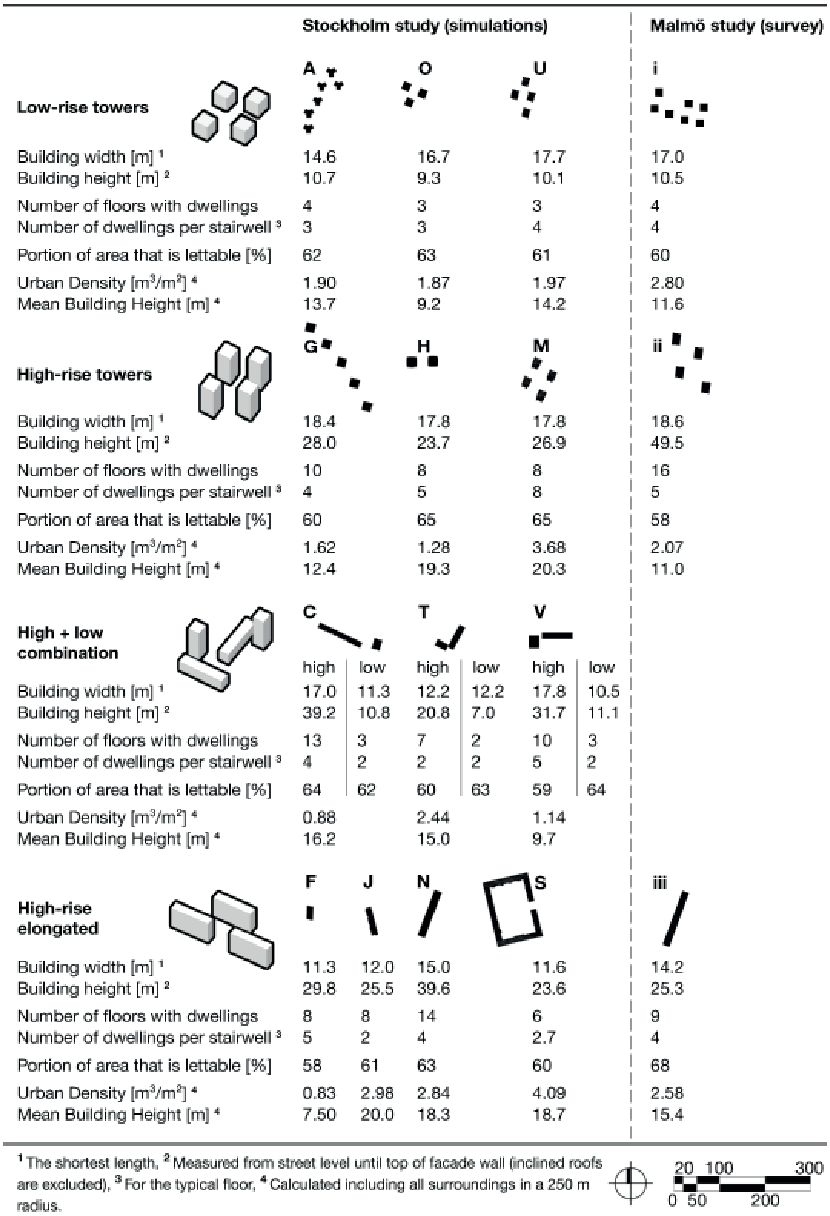


Figure 3.11 *Completed dwellings in newly constructed multi-dwelling buildings by year, for the ten largest municipalities in Sweden. Data retrieved from Statistics Sweden (SCB, 2020b). The municipalities in the legend are sorted from top to bottom according to their population on 31 December 2019.*

Figure 3.12 & 3.13 include summary data of the analysed developments. Developments “A-Y” were evaluated via simulations, and developments “i-vi” were surveyed. The indicator “portion of area that is lettable [%]” is calculated for the typical floor. It is the ratio of area requiring daylight provision (i.e. kitchens, living rooms, bedrooms, and dining rooms) to the total floor area. The indicator “urban density [m^3/m^2]” refers to surrounding obstructions. It expresses the magnitude of the total built volume [m^3] per site area [m^2], covering an area within a 250-m radius from each development. The indicator “mean building height [m]” also refers to surrounding obstructions, within the same range. It is the mean height of surrounding buildings, weighted by their footprint area. More details on geometric characteristics, e.g. room glass-to-floor ratio, depth, width etc. can be found for the samples of Stockholm and Malmö in Papers I & V respectively.



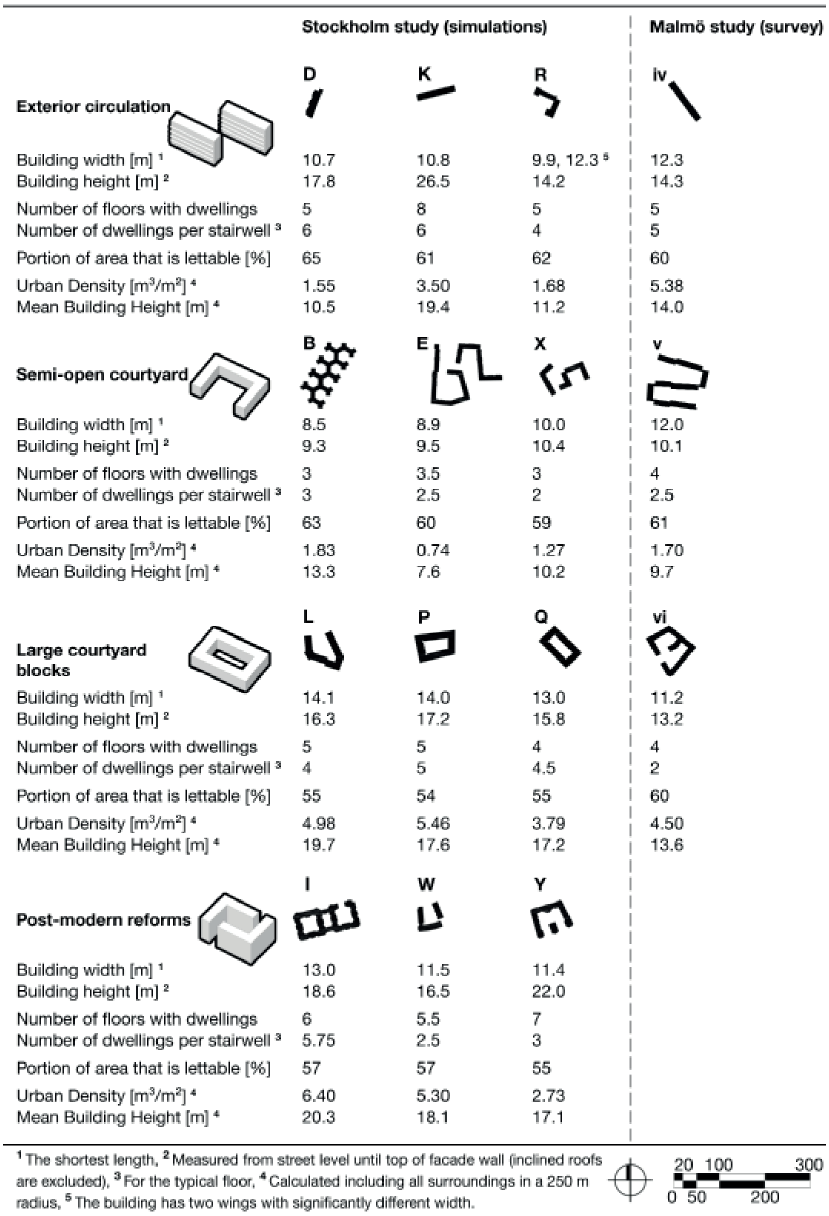
	Stockholm study (simulations)			Malmö study (survey)
Low-rise towers	**A**	**O**	**U**	**i**
Building width [m] [1]	14.6	16.7	17.7	17.0
Building height [m] [2]	10.7	9.3	10.1	10.5
Number of floors with dwellings	4	3	3	4
Number of dwellings per stairwell [3]	3	3	4	4
Portion of area that is lettable [%]	62	63	61	60
Urban Density [m^3/m^2] [4]	1.90	1.87	1.97	2.80
Mean Building Height [m] [4]	13.7	9.2	14.2	11.6
High-rise towers	**G**	**H**	**M**	**ii**
Building width [m] [1]	18.4	17.8	17.8	18.6
Building height [m] [2]	28.0	23.7	26.9	49.5
Number of floors with dwellings	10	8	8	16
Number of dwellings per stairwell [3]	4	5	8	5
Portion of area that is lettable [%]	60	65	65	58
Urban Density [m^3/m^2] [4]	1.62	1.28	3.68	2.07
Mean Building Height [m] [4]	12.4	19.3	20.3	11.0

High + low combination	**C**		**T**		**V**	
	high	low	high	low	high	low
Building width [m] [1]	17.0	11.3	12.2	12.2	17.8	10.5
Building height [m] [2]	39.2	10.8	20.8	7.0	31.7	11.1
Number of floors with dwellings	13	3	7	2	10	3
Number of dwellings per stairwell [3]	4	2	2	2	5	2
Portion of area that is lettable [%]	64	62	60	63	59	64
Urban Density [m^3/m^2] [4]	0.88		2.44		1.14	
Mean Building Height [m] [4]	16.2		15.0		9.7	

High-rise elongated	**F**	**J**	**N**	**S**	**iii**
Building width [m] [1]	11.3	12.0	15.0	11.6	14.2
Building height [m] [2]	29.8	25.5	39.6	23.6	25.3
Number of floors with dwellings	8	8	14	6	9
Number of dwellings per stairwell [3]	5	2	4	2.7	4
Portion of area that is lettable [%]	58	61	63	60	68
Urban Density [m^3/m^2] [4]	0.83	2.98	2.84	4.09	2.58
Mean Building Height [m] [4]	7.50	20.0	18.3	18.7	15.4

[1] The shortest length, [2] Measured from street level until top of facade wall (inclined roofs are excluded), [3] For the typical floor, [4] Calculated including all surroundings in a 250 m radius.

Figure 3.12 *Summary data for the Stockholm study developments (codes in Latin characters) and the Malmö study developments (codes in Latin numerals) classified into typologies: "low-rise towers", "high-rise towers", "high+low combination" and "high-rise elongated".*



	Stockholm study (simulations)			Malmö study (survey)
Exterior circulation	**D**	**K**	**R**	**iv**
Building width [m] [1]	10.7	10.8	9.9, 12.3 [5]	12.3
Building height [m] [2]	17.8	26.5	14.2	14.3
Number of floors with dwellings	5	8	5	5
Number of dwellings per stairwell [3]	6	6	4	5
Portion of area that is lettable [%]	65	61	62	60
Urban Density [m^3/m^2] [4]	1.55	3.50	1.68	5.38
Mean Building Height [m] [4]	10.5	19.4	11.2	14.0
Semi-open courtyard	**B**	**E**	**X**	**v**
Building width [m] [1]	8.5	8.9	10.0	12.0
Building height [m] [2]	9.3	9.5	10.4	10.1
Number of floors with dwellings	3	3.5	3	4
Number of dwellings per stairwell [3]	3	2.5	2	2.5
Portion of area that is lettable [%]	63	60	59	61
Urban Density [m^3/m^2] [4]	1.83	0.74	1.27	1.70
Mean Building Height [m] [4]	13.3	7.6	10.2	9.7
Large courtyard blocks	**L**	**P**	**Q**	**vi**
Building width [m] [1]	14.1	14.0	13.0	11.2
Building height [m] [2]	16.3	17.2	15.8	13.2
Number of floors with dwellings	5	5	4	4
Number of dwellings per stairwell [3]	4	5	4.5	2
Portion of area that is lettable [%]	55	54	55	60
Urban Density [m^3/m^2] [4]	4.98	5.46	3.79	4.50
Mean Building Height [m] [4]	19.7	17.6	17.2	13.6
Post-modern reforms	**I**	**W**	**Y**	
Building width [m] [1]	13.0	11.5	11.4	
Building height [m] [2]	18.6	16.5	22.0	
Number of floors with dwellings	6	5.5	7	
Number of dwellings per stairwell [3]	5.75	2.5	3	
Portion of area that is lettable [%]	57	57	55	
Urban Density [m^3/m^2] [4]	6.40	5.30	2.73	
Mean Building Height [m] [4]	20.3	18.1	17.1	

[1] The shortest length, [2] Measured from street level until top of facade wall (inclined roofs are excluded), [3] For the typical floor, [4] Calculated including all surroundings in a 250 m radius, [5] The building has two wings with significantly different width.

Figure 3.13 *Summary data for the Stockholm study developments (codes in Latin characters) and the Malmö study developments (codes in Latin numerals) classified into typologies: "exterior circulation", "semi-open courtyard", "large courtyard blocks" and "post-modern reforms".*

As can be seen on Figure 3.12, there are indications as to how different typologies may perform in terms of indoor daylight availability. “Low-rise towers” buildings are located in areas of relatively low urban density, and the mean building height of the surroundings is only one floor higher (e.g. for development “U”) or less. “High-rise towers” buildings are also located in areas of relatively low urban density, and are higher than their surroundings (building height > mean building height). “High + Low combination” buildings have a high part that is higher than the surroundings, and a low part that is narrow, except for development “T”, which is 12.2 m wide. “High-rise elongated” buildings have different widths, (as wide as 15 m), which implies that they have one- or two-aspect apartments, depending on width. One-aspect apartments in wide buildings may have the kitchen placed in the building core to provide fenestration for the rest of the rooms if the apartments include many rooms; this was actually the case with the selected “high-rise elongated” buildings, as they were constructed during an era of a high housing demand (section 3.1.2).

Hypotheses pertaining to indoor daylight availability can also be made by observing the data in Figure 3.13. “Exterior circulation” buildings provide a relatively large number of apartment units per staircase (4-6 units) as a result of the exterior balcony corridor, which may shade at least one lettable room as it extends along one of the two facades of the apartments. “Semi-open courtyards” are located in low-density building areas, with low surroundings. The buildings are very narrow, and have only a few apartment units per stairwell (2-3 units), which implies that most rooms have unobstructed windows. “Large courtyard blocks” and “Post-modern reforms” buildings are located in more densely built areas compared to the rest of the typologies (urban density indicator). In addition, we can assume that self-shading will occur for a number of rooms facing the courtyard side or facing surroundings at a close distance, due to the strict city planning grid in these areas.

3.2 Daylight simulations

Daylight simulations were performed to assess the selected developments “A-Y” in terms of daylight compliance. This chapter includes an overview of the main components of daylight simulations, brief descriptions of the daylight metrics and evaluation criteria considered, and notes on the simulation tools used to calculate indoor illuminance levels.

3.2.1 Fundamental elements of daylight simulation

While different software tools might ask the user for different input through their respective interfaces, there is always a fundamental set of underlying elements to be specified in order to conduct a daylight simulation. Reinhart (2011) has made a clear categorisation of these elements and a schematic map of a daylight simulation program, similar to Figure 3.14. The following are brief descriptions of the underlying elements of a daylight simulation program:

- The scene. The geometrical model of the three-dimensional space under investigation, where object surfaces have been assigned with materials of specific optical properties. For this thesis, this corresponds to the evaluated multi-dwelling developments, the surrounding buildings and trees, and the ground surface.
- The sky model. A quantification of the amount of both direct and diffuse light, originating from different areas (patches) of the hemispherical sky dome. For this thesis, two sky models were used, depending on the type of simulation, i.e. on whether it was a point-in-time or an annual simulation. Point-in-time simulations were performed using a CIE Standard Overcast sky model (CIE, 2004), and annual simulations were performed using the Perez All-Weather sky luminance model (Perez et al., 1993) discretised by approximating the celestial hemisphere to a series of luminous patches per hour of the year according to Subramaniam and Mistrick (2017).
- The analysis area. The part of the scene where daylight analysis will take place. There are two main types of analysis: 1) an image-based evaluation where surface luminance is assessed for an observer, i.e. the analysis area is surfaces in the field of view, and 2) a grid-based evaluation where illuminance is calculated on a surface or plane, i.e. the analysis area is a user-specified grid of points. The latter type was deployed for this thesis.
- Space usage. Information on space function (office, school, residential, etc.). Depending on space usage, different occupancy schedules apply, and different lighting levels are required. Since multi-dwelling buildings may not exhibit strict occupancy patterns similar to office buildings (e.g. from 9:00-17:00), annual simulations for this thesis were performed accounting for portions of daylight hours of the year, which is similar to the convention of the European standard EN-17037 (CEN, 2018b).

- Simulation engine. The daylight calculation algorithm that merges the scene with the sky model to calculate daylight (illuminance or luminance) for the specified analysis area. This part of the simulation process executes a "global illumination algorithm", which mimics light propagation in space via reflection, transmittance, and refraction. This thesis used software tools that deploy raytracing, which is a widely used global illumination algorithm in the field of daylight simulations. The tools used are described in section 3.2.4.
- Results processor. A post-simulation process where raw illuminance or luminance results are translated into the format of daylight metrics that can easily inform the user on whether the desired daylight conditions are met. For example, calculated illuminance can be transformed into a Daylight Factor percentage. The processor retrieves raw results from the simulation engine and outputs daylight metric values, for evaluation according to standards and recommendations.

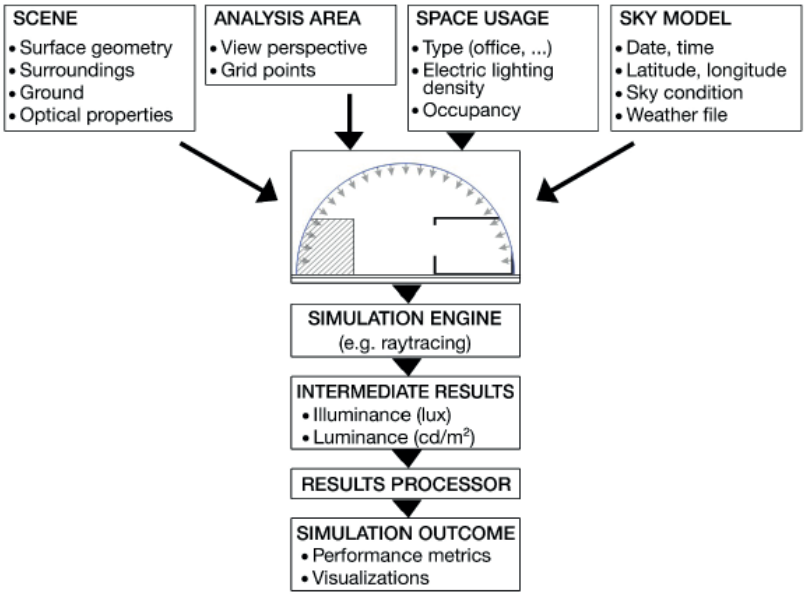


Figure 3.14 *Schematic map illustrating the fundamental elements of daylight simulations. Image inspired by C. F. Reinhart (2011).*

The scene, the sky model and the simulation engine are elements that the user must set carefully, to ensure an accurate reproduction of reality, in other words, to produce results that are predictive of the way the real space would appear. These elements are crucial only in synthesising a simulation model. On the other hand, the decision-making element that will streamline the design process is the results processor. The post-processing of results at this stage is particularly important as it defines the performance indicator, i.e. the metric with which daylight availability is measured. Consequently, compliance criteria can be formulated by setting thresholds for metrics, to determine whether a space is performing well or not. Care should be taken in the selection of the metrics and compliance criteria, as they can dictate which design solutions are discarded in favour of "compliant" solutions, thereby affecting the work of practitioners and the final product of architectural design.

For the purpose of this thesis, several daylight criteria were considered in order to assess the compliance of multi-dwelling buildings. Different criteria utilise different daylight metrics. Criteria and metrics should not be confused. According to Mardaljevic et al. (2009), "a metric is some mathematical combination of (potentially disparate) measurements and/or dimensions and/or conditions represented on a continuous scale (…). A criterion is a demarcation on that metric scale that determines if something passes or qualifies, e.g. three-quarters of the workspace area achieves a 2 % daylight factor". The following sections include brief descriptions of the metrics and criteria that were considered in this thesis.

3.2.2 Daylight metrics considered in this thesis

The definitions of all daylight metrics considered in this thesis are described below:

Illuminance (E) at a point of a surface:	Quotient of the luminous flux dΦv incident on an element of the surface containing the point, by the area dA of that element (CEN, 2018a). Unit: lx = lumen per m^2
Uniformity ratio (U):	The ratio of minimum to average illuminance on a surface (CEN, 2018a). Unit: dimensionless
Daylight Factor (DF):	The ratio of internal to unobstructed horizontal illuminance under a CIE Standard Overcast sky model (Hopkinson, 1963), usually expressed as a percentage. The luminance of the CIE Standard Overcast sky model is rotationally symmetrical about the vertical

	axis, and is three times higher at the zenith compared to the horizon. The model does not include the sun, which means that the DF is not sensitive to façade orientation. When calculated on a single point, the DF can be referred to as a Point Daylight Factor, similar to the $\mathrm{DF_P}$ metric of the current Swedish daylight regulation (SIS, 1988). If measured across a grid of points on a plane, the average DF and the median DF values can be calculated. Unit: %
Useful Daylight Illuminance (UDI):	The annual occurrence of illuminances across a plane that fall within a "useful" range for occupants (Nabil and Mardaljevic, 2005). The rationale is that low illuminance levels will trigger electric lighting use, while extremely high illuminances may hinder particular tasks and trigger the use of shading, thereby deeming illuminance "useful" only within a certain range. The range has so far been defined for office spaces, and lies between 100 lx and 3000 lx (Mardaljevic et al., 2012). This range corresponds to the scheme referred to as *UDI combined*. It accounts for the combined illuminance ranges of 100-300 lx, i.e. *UDI supplementary* (or UDI-s), and 300-3000 lx, i.e. *UDI autonomous* (or UDI-a). Unit: % of occupancy time

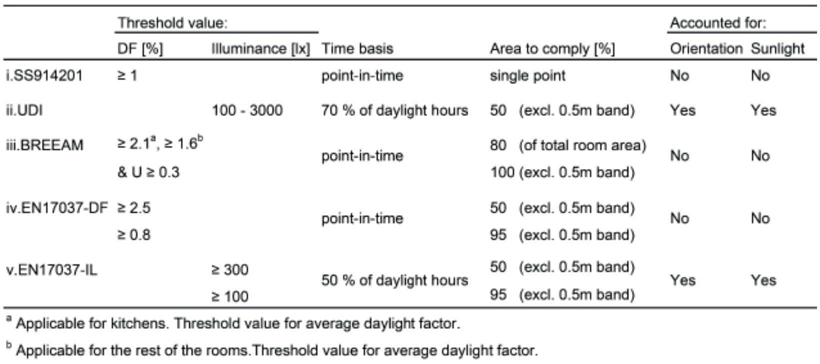
3.2.3 Daylight criteria considered in this thesis

The daylight compliance of the investigated multi-dwelling buildings was assessed according to different criteria. Overall, the criteria differ in the metrics used, the analysis areas, the assumptions for occupancy time (time basis), and the target illuminance levels (Table 3.1). Explicit descriptions of the criteria can be found under section 2.3 of Paper III. The criteria considered included:

- The glass-to-floor ratio compliance criterion (GFR ≥ 10 %).
- The Point Daylight Factor compliance criterion (SS914201).
- The Useful Daylight Illuminance compliance criterion (UDI).

- The BREEAM-SE good practice daylight factor criterion (BREEAM).
- The European standard compliance criterion that is based on the daylight factor method (EN17037-DF).
- The European standard compliance criterion that is based on the illuminance method (EN17037-IL).

Table 3.1 Summary of criteria that consider illumination, including threshold values, time bases, areas to comply, and other considerations (orientation, sunlight). The column "Area to comply [%]" indicates the analysis area considered, and specifies whether a 0.5-m band off walls is excluded (excl.) from the evaluation or not.



	Threshold value:				Accounted for:	
	DF [%]	Illuminance [lx]	Time basis	Area to comply [%]	Orientation	Sunlight
i.SS914201	≥ 1		point-in-time	single point	No	No
ii.UDI		100 - 3000	70 % of daylight hours	50 (excl. 0.5m band)	Yes	Yes
iii.BREEAM	≥ 2.1[a], ≥ 1.6[b] & U ≥ 0.3		point-in-time	80 (of total room area) 100 (excl. 0.5m band)	No	No
iv.EN17037-DF	≥ 2.5 ≥ 0.8		point-in-time	50 (excl. 0.5m band) 95 (excl. 0.5m band)	No	No
v.EN17037-IL		≥ 300 ≥ 100	50 % of daylight hours	50 (excl. 0.5m band) 95 (excl. 0.5m band)	Yes	Yes

[a] Applicable for kitchens. Threshold value for average daylight factor.

[b] Applicable for the rest of the rooms.Threshold value for average daylight factor.

3.2.4 Daylight simulation tools used in this thesis

The engine that performs daylight simulations deploys a specific global illumination algorithm to calculate light contributions from light sources to evaluation points (analysis areas). Although there are a number of existing algorithms that deploy different approaches to calculate light transport, in essence all algorithms are approximations to the "rendering equation" presented by Kajiya (1986), which is a unifying equation to calculate the total luminous flux outgoing from a surface point, accounting for the surface optical properties and the incoming flux onto the point from different directions. Existing algorithms include radiosity (Goral et al., 1984), raytracing (Whitted and Foley, 1980) and photon mapping (Jensen, 1996), each with different capabilities and limitations. A raytracing algorithm was used for this thesis, namely the Radiance backward raytracer (Ward and Shakespeare, 1998), originally written by Greg Ward at Lawrence Berkley National Laboratory. The reasons for using Radiance in this thesis were: 1) it has been extensively and independently validated (Aizlewood et al., 1998; Jarvis and Donn, 1997; Mardaljevic, 1995; Ubbelohde and Humann, 1998), 2) it is free to use and open source, 3) it is under constant development and refinement by international research, 4) it is the underlying algorithm of a multitude of simulation tools used by practitioners of daylight simulations, and 5) it can be used in tandem with thermal comfort and energy simulations if the need arises.

Radiance was used through the interfaces provided by Grasshopper plugins Honeybee (legacy) (Sadeghipour Roudsari and Pak, 2013) and Honeybee (plus) (Sadeghipour Roudsari and Subramaniam, 2016). Honeybee (legacy) was used to calculate point-in-time metrics, in this case daylight factors, while Honeybee (plus) was used to derive climate-based metrics, i.e. metrics derived from calculated illuminance time-series. The reason for this differentiation is that Honeybee (plus) offers a more accurate calculation model for annual simulations, as it utilises different Radiance executables that treat direct solar contributions with a higher spatial accuracy compared to Honeybee (legacy) (Subramaniam and Mistrick, 2017), which uses the Daysim sky division scheme for direct solar position resolution (Reinhart, 2001). The surface optical properties used in simulations included standard values (CEN, 2018b; IES, 2012). The corresponding Radiance rendering settings per simulation type (point-in-time or annual) and the surface properties assumed for all simulations can be found in Paper III, section 2.2, Table 1. Geometry modelling assumptions can be found in Paper II, section 2.3.1.

3.3 Daylight survey

The daylight survey was distributed to collect subjective responses on daylight conditions inside the selected multi-dwelling buildings, with the aim to complement the simulation study with subjective evaluations from occupants. The survey was based on self-administered questionnaires, which were sent by normal mail to the civic addresses of the occupants. The overall design of the survey is illustrated in Figure 3.15. The data acquisition steps included: i) selecting housing developments, ii) distributing questionnaires to occupants living in these developments, and iii) collecting responses from occupants that chose to participate in the survey. The post-processing steps included: iv) locating the apartment of each participant, v) characterising each apartment geometrically, and vi) analysing responses with respect to apartment geometry and occupant characteristics.

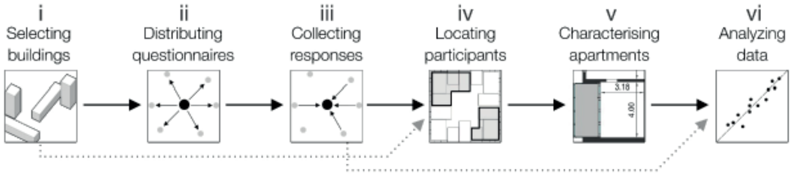


Figure 3.15 *Schematic representation of the survey design, illustrating the six procedural steps followed.*

3.3.1 Survey period and subjects

The survey was carried out during spring 2018, in six multi-dwelling developments in Malmö (latitude: 55.6 °N). The majority of participants (90 %) gave their responses between March 14 and March 28 (Figure 3.16). The response rate was calculated to 13 % (n = 108), but it was confirmed that there was satisfactory variation in age and gender among participants (Figure 3.17). Details on the response rate calculation and justification on the selection of this time period can be found in Paper IV, sections 2.4 & 2.5.

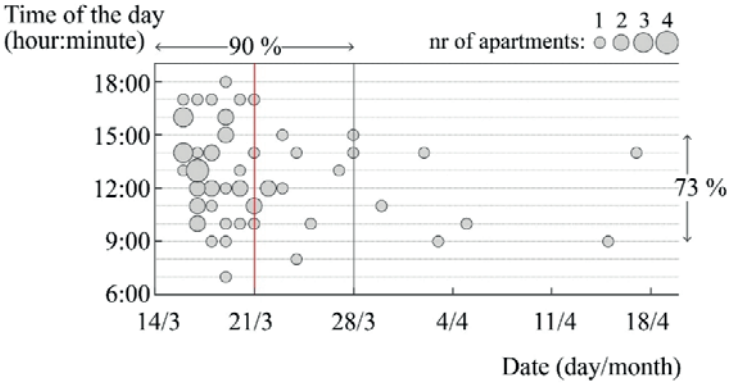


Figure 3.16 *Date and time of participation, and number of apartments per day and hour.*

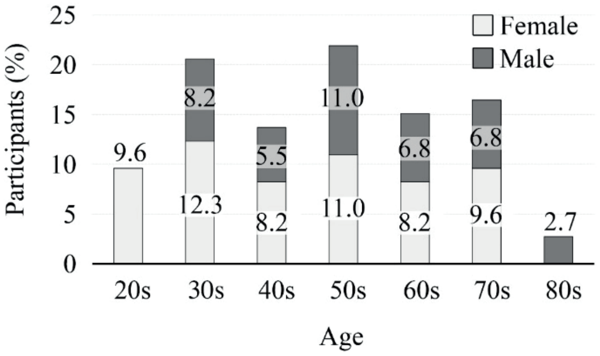
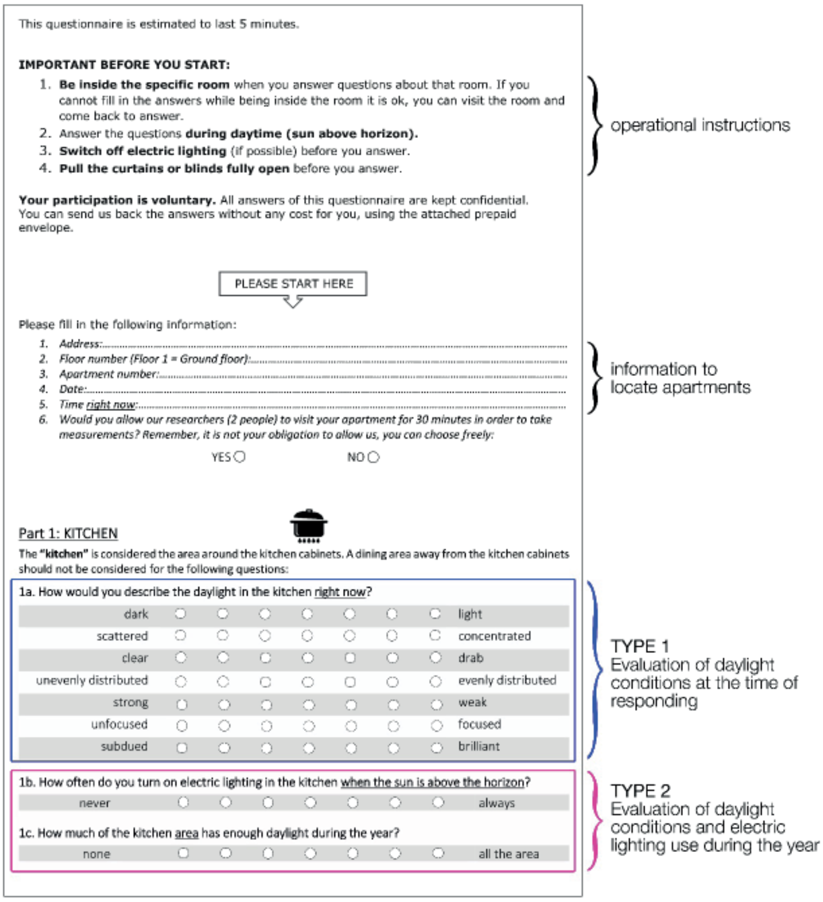


Figure 3.17 Percentage of participants per age group and gender.

3.3.2 Questionnaire structure

The questionnaire structure is shown in Figures 3.18 & 3.19 (questionnaire pages 1 & 2 respectively), which present the English translation of the questionnaire. There were two additional translations (Swedish and Arabic) with the aim to increase the response rate, but all participants (n = 108) used the Swedish translation. The reader may find the Swedish translation of the questionnaire online, in the supplemental material of Paper VI (published under an open access licence); this was the translation used by all participants. The questionnaire entailed different sections, as marked in Figures 3.18 & 3.19. The first half-page contained operational instructions and fields for apartment data that were necessary to locate the apartments (Figure 3.15, step iv). The rest of the questionnaire included questions pertaining to daylight conditions, electric lighting use, and occupant preferences. The questions were focused on kitchens (K), living rooms (L) and bedrooms (B). The main part of the questionnaire required occupants to make two types of evaluations: 1) evaluation of daylight conditions during the survey (TYPE 1), and 2) evaluations of daylight conditions and electric lighting use during the whole year (TYPE 2). Additionally, at the end of the questionnaire (page 2, Part 4), a third type of evaluation was included, which concerned occupant preferences (TYPE 3).



This questionnaire is estimated to last 5 minutes.

IMPORTANT BEFORE YOU START:

1. **Be inside the specific room** when you answer questions about that room. If you cannot fill in the answers while being inside the room it is ok, you can visit the room and come back to answer.
2. Answer the questions **during daytime (sun above horizon).**
3. **Switch off electric lighting** (if possible) before you answer.
4. **Pull the curtains or blinds fully open** before you answer.

Your participation is voluntary. All answers of this questionnaire are kept confidential. You can send us back the answers without any cost for you, using the attached prepaid envelope.

PLEASE START HERE

Please fill in the following information:

1. *Address:*……………………………………………
2. *Floor number (Floor 1 = Ground floor):*……………………………
3. *Apartment number:*……………………………………
4. *Date:*……………………………………………
5. *Time right now:*……………………………………
6. *Would you allow our researchers (2 people) to visit your apartment for 30 minutes in order to take measurements? Remember, it is not your obligation to allow us, you can choose freely:*

YES ○ NO ○

Part 1: KITCHEN

The **"kitchen"** is considered the area around the kitchen cabinets. A dining area away from the kitchen cabinets should not be considered for the following questions:

1a. How would you describe the daylight in the kitchen right now?

dark	○	○	○	○	○	○	○	light
scattered	○	○	○	○	○	○	○	concentrated
clear	○	○	○	○	○	○	○	drab
unevenly distributed	○	○	○	○	○	○	○	evenly distributed
strong	○	○	○	○	○	○	○	weak
unfocused	○	○	○	○	○	○	○	focused
subdued	○	○	○	○	○	○	○	brilliant

1b. How often do you turn on electric lighting in the kitchen when the sun is above the horizon?

never	○	○	○	○	○	○	○	always

1c. How much of the kitchen area has enough daylight during the year?

none	○	○	○	○	○	○	○	all the area

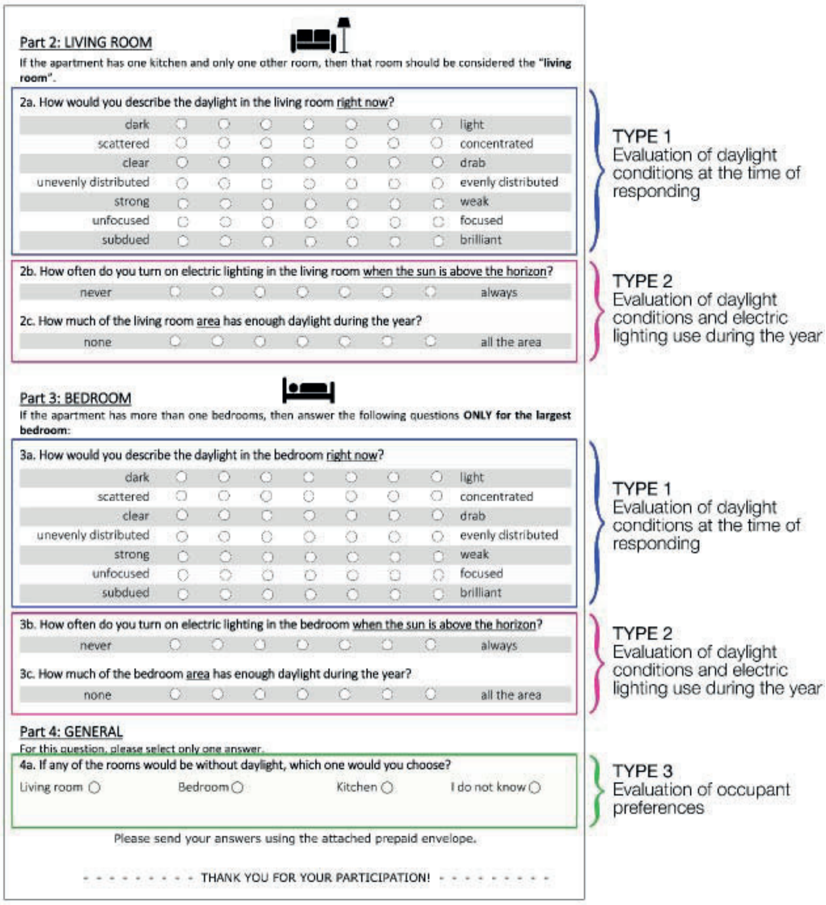
operational instructions

information to locate apartments

TYPE 1
Evaluation of daylight conditions at the time of responding

TYPE 2
Evaluation of daylight conditions and electric lighting use during the year

Figure 3.18 First page of the questionnaire, translated into English.



Part 2: LIVING ROOM

If the apartment has one kitchen and only one other room, then that room should be considered the **"living room"**.

2a. How would you describe the daylight in the living room right now?

dark	○	○	○	○	○	○	○	light
scattered	○	○	○	○	○	○	○	concentrated
clear	○	○	○	○	○	○	○	drab
unevenly distributed	○	○	○	○	○	○	○	evenly distributed
strong	○	○	○	○	○	○	○	weak
unfocused	○	○	○	○	○	○	○	focused
subdued	○	○	○	○	○	○	○	brilliant

TYPE 1
Evaluation of daylight conditions at the time of responding

2b. How often do you turn on electric lighting in the living room when the sun is above the horizon?

never	○	○	○	○	○	○	○	always

2c. How much of the living room area has enough daylight during the year?

none	○	○	○	○	○	○	○	all the area

TYPE 2
Evaluation of daylight conditions and electric lighting use during the year

Part 3: BEDROOM

If the apartment has more than one bedrooms, then answer the following questions **ONLY for the largest bedroom**:

3a. How would you describe the daylight in the bedroom right now?

dark	○	○	○	○	○	○	○	light
scattered	○	○	○	○	○	○	○	concentrated
clear	○	○	○	○	○	○	○	drab
unevenly distributed	○	○	○	○	○	○	○	evenly distributed
strong	○	○	○	○	○	○	○	weak
unfocused	○	○	○	○	○	○	○	focused
subdued	○	○	○	○	○	○	○	brilliant

TYPE 1
Evaluation of daylight conditions at the time of responding

3b. How often do you turn on electric lighting in the bedroom when the sun is above the horizon?

never	○	○	○	○	○	○	○	always

3c. How much of the bedroom area has enough daylight during the year?

none	○	○	○	○	○	○	○	all the area

TYPE 2
Evaluation of daylight conditions and electric lighting use during the year

Part 4: GENERAL

For this question, please select only one answer.

4a. If any of the rooms would be without daylight, which one would you choose?

Living room ○ Bedroom ○ Kitchen ○ I do not know ○

TYPE 3
Evaluation of occupant preferences

Please send your answers using the attached prepaid envelope.

- - - - - - - - - THANK YOU FOR YOUR PARTICIPATION! - - - - - - - - -

Figure 3.19 *Second page of the questionnaire, translated into English.*

The procedure used to collect TYPE 1 and 2 evaluations was category rating, by means of semantic differential (SD) scales. TYPE 1 scales were developed by previous research (Küller and Wetterberg, 1993; Küller and Wetterberg, 1996), and were used here to measure perceived brightness and distribution of light. Methodological details regarding these scales are given in Paper IV, section 2.6. TYPE 2 scales were developed specifically for this thesis, with the intent to derive a measure of daytime electric lighting use and a measure of perceived spatial brightness during the year. Methodological details regarding TYPE 2 scales are given in Paper VI, section 2.3. For TYPE 3, a multiple-choice question with a single-answer option was provided, with the intent to assess which room is not prioritised in terms of indoor daylight levels. The design of this question is elaborated in Paper VI, section 2.3.7.

4 Summary of the appended papers

This section provides a brief summary of the appended papers, including research questions and findings per paper. The first three papers (Papers I-III) investigate daylight compliance of multi-dwelling buildings via simulations. The last three papers (Papers IV-VI) analyse survey responses regarding daylight conditions and daytime lighting use. The research work considered multiple variables associated with urban density, geometry, and occupant response (Table 4.1). Urban density and geometry are determinants of daylight availability, while occupant responses are assessors of its adequacy. Table 4.1 shows which variables are analysed per article. In essence, if one article includes variables of two categories (e.g. Paper VI: geometry and occupant responses), this indicates that the relation between the two categories is examined in the article.

Table 4.1 Variables included in the scope of each appended paper. The parameters are grouped in three main factors pertaining to indoor daylight availability: urban density, geometry, and occupant responses.

		Paper					
	Variable:	I	II	III	IV	V	VI
Urban density	Mean building height		X	X			
	Urban density	X	X	X			
	Obstruction angle	X					
	Vertical Sky Component			X	X		
Geometry	Construction year	X	X				
	Block typology		X	X		X	
	Room function	X		X		X	X
	Room area		X	X	X		
	Room depth	X	X	X	X		
	Room width	X	X	X			
	Room height	X					
	Room orientation					X	X
	Room external wall area		X				
	Balcony shading	X			X		X
	Number of fenestrated walls				X		
	Windowless room	X					
	Glazing area			X	X		
	Glazing width	X					
	Glazing height	X					
	Window-to-wall ratio	X					
	Glass-to floor ratio	X		X	X		X
	Glass-to-wall ratio			X	X		X
	Glass-to-internal-wall ratio			X	X		X
Occupant response	Age						X
	Brightness response				X		
	Distribution response				X		
	Daytime lighting use response					X	X
	Daylit area response						X
	Room prioritisation response						X

Paper I includes a historic review of Swedish daylight regulations, and a comparison between the two assessment methods currently used in Sweden to test compliance. Papers II & III investigate daylight compliance and the effect of building typology, room geometry, urban density, and evaluation criterion. Paper IV assesses the suitability of TYPE 1 questions (Figures 3.18 & 3.19) for measuring perceived brightness, and whether the measurement is associated with geometric characteristics of rooms. Paper V assesses whether room geometry, function, and orientation are determinants of frequent daytime lighting use in dwellings or not. Paper VI assesses the degree of association between daytime lighting use and perceived daylight levels, and evaluates which rooms are prioritised by occupants in terms of indoor daylight availability. The following sections provide the main research questions, methods, and findings per article.

4.1 Paper I – Swedish daylight regulation throughout the 20th century and considerations regarding current assessment methods for residential spaces

Paper I reviews the evolution of daylight evaluation criteria in Sweden from 1960 until the present day, finding the country with two criteria in force, the DF_P method and the GFR-method. The study proceeds by analysing different aspects relating to these criteria: it assesses whether the introduction of quantified criteria improved the daylight performance of buildings or not, it compares the two criteria with respect to the compliance they yield for different rooms, and it highlights assessment limitations for each criterion. The study informs on whether the current criteria are applicable for residential spaces or not and whether they are limited in assessing specific designs, two aspects that may reveal the need for new criteria today.

Research questions:

1. What is the evolution of daylight evaluation criteria stipulated by the Swedish building code in the 20th century?
2. Did the introduction of quantified daylight evaluation criteria improve the performance of multi-dwelling buildings historically?
3. Is the current glazing-area assessment method (GFR-method) applicable in residential buildings?
4. Do the two criteria agree in terms of the compliance they yield for residential rooms?

Methods:

The study consisted of four methodological steps: 1) a literature review including building regulations from 1960 onwards, 2) a systematic record of room characteristics derived from building documentation drawings, 3) computer simulations of individual room scenes (n = 10888), and 4) statistical analysis. For the literature review, the study focused on the timespan after the introduction of evaluation criteria that were numerical, i.e. quantified. The surveyed characteristics of rooms included geometry measures referenced in regulations, namely room depth, width and height, and glass width, height, and obstruction angle. Simulations were performed using the Radiance backward raytracer, assuming a standard set of optical properties for room surfaces and surrounding obstructions. The data analysis included descriptive statistics to evaluate the applicability of the GFR-method, and inferential statistics with hypothesis testing to compare the compliance of rooms from different eras and to assess the degree of agreement between the current two criteria.

Answers to the research questions:

1. Daylighting criteria effectively came into force in 1975. Since then, their formulation has iterated between a daylight factor and a glazing-area criterion. In essence, the current daylight factor criterion is not different to the one formulated in 1975.
2. Buildings erected following the introduction of quantified daylight performance criteria do not necessarily outperform their predecessors.
3. The current glazing-area criterion is not applicable in most rooms considered in this thesis. It was inapplicable in 3 out of 4 rooms in the selected residential building sample.
4. The current criteria yielded the same compliance (pass or fail) for 87 % of the evaluated rooms. For the rest of the rooms, the glazing-

area criterion was easier to comply with, compared to the daylight factor-based criterion.

4.2 Paper II – Daylight regulation compliance of existing multi-family apartment blocks in Sweden

Paper II elaborates on the effect of building form on room compliance with the current $DF_P \geq 1$ % criterion. The study aims to give a general picture of the compliance of the current building stock, and to identify typologies that perform well or poorly. In addition, the paper shows which daylight factor-based metrics yield values similar to DF_P, and what geometric measures are associated with them. A note is also added with respect to the association between daylight compliance and urban density.

Research questions:

1. What is the compliance level of the current building stock?
2. What typologies have a higher potential for compliance?
3. What other daylight factor metric yields similar compliance with DF_P?
4. Does urban density affect daylight compliance?

Methods

The study consisted of three methodological steps: 1) selection and geometric modelling of spaces representative of residential architecture, 2) computer simulations of individual room scenes (n = 10888) to derive daylight performance, and 3) data analysis. The selection of buildings was based on 1) typology and 2) construction year. The geometric modelling followed documentation drawings retrieved from the municipal drawings archive of Stockholm. Similar to Paper I, daylight simulations were performed using the Radiance backward raytracer, assuming a standard set of optical properties for room surfaces and surrounding obstructions. Only “static” daylight performance metrics were calculated. Data analysis included descriptive statistics. More specifically, the percentage of DF_P-compliant rooms in each typology and building were calculated and compared to examine the performance of the overall building sample, and to compare different typologies. In addition, DF_P was compared to average and median daylight factors calculated for the same spaces to identify similarities between "static" daylight metrics and possible alternatives to DF_P. Daylight compliance according to DF_P was also associated (Spearman) with urban density to identify any overarching association between daylight compliance and surrounding obstructions.

Answers to the research questions:

1. Only 13 out of 54 buildings complied with the current criterion of $DF_P \geq 1$ %.
2. "Semi-open courtyards", "high-rise towers", "low-rise towers" and "high + low combinations" were found to be more compliant overall.
3. The median daylight factor of a grid of points across the floor area (excluding a 0.5 m band off walls) correlated very strongly with DF_P.
4. Density was found to associate strongly with DF_P compliance.

4.3 Paper III – Daylight compliance of residential spaces: Comparison of different performance criteria and association with room geometry and urban density

Paper III expands the scope of Paper II, as it investigates multiple daylight evaluation criteria. Different typologies and room functions are compared with respect to their compliance with each criterion, and geometric measures and urban density are associated with the degree of compliance per criterion. The criteria are also compared with respect to the compliance they yield, to identify differences and similarities stemming from their formulations. The study provides information that can be useful for policymakers in their selection of appropriate compliance criteria for residential spaces.

Research questions:

1. Does the choice of compliance criterion affect which typology ranks higher in terms of compliance?
2. Is there a criterion that yields similar compliance compared to the current Swedish criterion?
3. Do the two assessment methods found in European standard EN-17037 yield similar compliance?

4. Which geometric measures affect compliance more substantially?
5. Which criterion best reflects the degree of surrounding obstructions?

Methods

The method followed for this article builds on methods used in Papers I and II, as it investigates the same building sample and processes data from the same room geometry database. Additional methods included 1) computer simulations to derive climate-based daylight metrics, and 2) data analysis according to the new research questions. The study presents five daylight compliance criteria stipulated by either building standards or certification schemes and proceeds with compliance-testing on the building sample according to each criterion. The criteria included the current Swedish DFp criterion, the two performance criteria set by European standard EN-17037, the daylight factor-based criterion of BREEAM, and a climate-based criterion founded on the UDI metric. Daylight performance is evaluated using each criterion at three levels, namely typology, building, and room level, to identify whether performance is independent of the criterion used or not. Different criteria are compared for the compliance they yield for the same rooms, to identify which criteria agree or disagree substantially. All criteria are associated with room geometry to identify the most influential geometric factors of compliance, and are compared based on the degree they relate to urban density. Data analysis included hypothesis testing to make inferences to the general building stock, and focused on effect size calculations and probability testing.

Answers to the research questions:

1. Typologies rank differently when tested against different criteria. However typologies with heavily shaded apertures (“large courtyard blocks”, “post-modern reforms” and “exterior circulation”) rank consistently low.
2. The UDI criterion was shown to have the highest agreement with the current Swedish criterion. This is interesting, as the UDI criterion can upgrade the current assessment to ‘climate-aware’ level.
3. The two assessment methods of standard EN-17037 yield significantly different compliance, with the daylight factor-based criterion being much harder to comply with.
4. Of the evaluated geometric measures, Glass-to-Floor Ratio and Vertical Sky Component were significantly higher in compliant than in incompliant rooms.
5. Urban density was shown to correlate stronger with compliance according to UDI compared to other criteria.

4.4 Paper IV – Perceived daylight conditions in multi-family apartment blocks – Instrument validation and correlation with room geometry

Paper IV processes survey responses on brightness and daylight distribution in 225 rooms of 6 multi-dwelling buildings in the city of Malmö (latitude: 55.6 °N). The buildings were selected to be representative of residential spaces, and were chosen to belong to the same typological categories as the ones selected for the simulation studies in Papers I, II and III. Responses were measured using an observer-based environmental assessment instrument (OBEA) consisting of semantic differential scales. The scales were post-processed to derive any reliable measurement of subjective perception of brightness and daylight distribution. Overall, the study validated whether these scales are reliable for use in questionnaires pertaining to daylight evaluations, and whether occupant responses regarding room brightness relate to room geometry.

Research questions:

1. Is the OBEA instrument reliable and valid for measuring perceived brightness and daylight distribution in residential spaces?
2. Is the measurement of the instrument associated with room geometry?

Methods

The study used self-administered questionnaires that were sent by post in mid-March 2018, and 75 questionnaires were returned without missing values. Each questionnaire included separate responses for the kitchen, living room, and largest bedroom of the apartment. The responses were given on semantic scales that consist of bipolar adjectives such as Bright – Dark, Strong – Weak etc. Occupants used four scales to report room brightness, and three to report daylight distribution. During the survey, the global horizontal irradiance was monitored using a Kipp&Zonen CM-11 pyranometer. Using exploratory factor analysis on the four scales pertaining to Brightness, the study derived one component ("Brightness", Cronbach's alpha = 0.89) and validated it by associating it with global horizontal irradiance (Spearman's r_S = 0.566, p = 0.006). Subsequently, the component was correlated with attributes such as the glazing area, glass-to-floor ratio, Vertical Sky Component, etc., to examine whether room geometry relates to occupant responses or not.

Answers to the research questions:

1. The OBEA used was shown to be a reliable and valid instrument for measuring brightness perception. The scales pertaining to daylight distribution did not present adequate internal reliability.
2 The Brightness measurement was found to associate with room glass-to-floor ratio (GFR), in particular, rooms with GFR ≥ 10 % were perceived as being brighter than rooms with GFR < 10 %. An association with other geometric measurements could not be established as the effect of solar irradiation could not be isolated due to study design limitations. Therefore, it is not possible to ascertain whether the questionnaire measurement relates to specific geometry measurements or not.

4.5 Paper V – Residential electric lighting use during daytime: A field study in Swedish multi-dwelling buildings

The main aim of Paper V is to evaluate whether room function and room orientation have an impact on daytime electric lighting use in residential spaces. The study processes the same questionnaires that were used in Paper V, but focused on a single response scale. The scale ranged from 1 to 7, and was used by occupants to respond to the question: "How often do you turn on electric lighting in the kitchen/living room/bedroom when the sun is above the horizon?". Statistical analysis was used to correlate the measurement with 1) measures of room geometry, 2) categories of room function, and 3) façade orientation. The results can be useful for the inception of future design guidelines for dwellings, for instance guidelines that differentiate between room functions.

Research questions:

1. Does room geometry impact daytime lighting use?
2. Does room function impact daytime lighting use?
3. Does room orientation impact daytime lighting use?

Methods

The study processed 108 responses regarding frequency of electric lighting use during the day (daytime lighting use), to evaluate whether it is affected by room function and orientation, and whether geometry plays a confounding role. In a preliminary step, the behaviour of occupants regarding electric lighting use was evaluated, to test whether design and orientation can affect switch-on behaviour or whether it is random and unpredictable. In the main part of the study, statistical analysis was performed to verify whether there is a relation between daytime electric lighting and room function, room orientation, or both. The data were analysed using 1) descriptive statistics to observe frequencies of responses for different categories of room type and orientation, and 2) hypothesis-testing to examine significant differences between categories.

Answers to the research questions:

1. Room geometry impacts daytime lighting use to a certain extent. The study showed that different occupants living in similarly designed rooms reported similar daytime lighting use.
2. During daytime, it is generally common for electric lighting to be used in kitchens more frequently compared to the rest of the rooms. However, it was shown that room function per se is not the cause of this. When comparing rooms of different functions but of similar geometry and surroundings, the reported lighting use did not differ between functions.
3. Room orientation was found to impact daytime lighting use. West-oriented rooms reported significantly less frequent daytime lighting use, especially compared to east-oriented rooms.

4.6 Paper VI – Association between perceived daylit area and self-reported frequency of electric lighting use in multi-dwelling buildings.

Paper VI cross-references occupant responses on 1) daytime lighting use and 2) perceived extent of daylit area, with the aim to investigate an association between the two. In addition, the paper processes responses pertaining to occupant preferences, in particular which room they would not prioritise in terms of daylight availability if they had to choose one such room. The outcome of this study can serve as evidence that electric lighting use is not random in dwellings, but that it can be dictated by design, and therefore by design guidelines.

Research questions:

1. Do occupants use lighting less frequently if their dwellings are perceived as adequately daylit?
2. In which room would occupants tolerate inadequate daylight levels?

Methods

The study focuses on the association between two responses given by occupants: 1) how often they use electric lighting during daylight hours (EL), and 2) how much of the floor area they perceive as adequately daylit (DA) throughout the year. Responses EL and DA were measured on seven-point semantic differential scales, and were correlated (Spearman) to evaluate their association for different room groups. Groups were based on age, room function, façade orientation, balcony obstruction, and fenestration geometry. A third response (PR), pertaining to occupant preferences, was also analysed. This response was given on a multiple-choice question with a single-answer option. Occupants were asked which room they would choose if there had to be one underlit room, and they could respond with either one of the following: "kitchen", living room", "bedroom", or "I don't know which one". Overall, the study used descriptive statistics and hypothesis-testing wherever applicable in order to verify the significance of the findings.

Answers to the research questions:

1. Daytime lighting use was shown to correlate strongly with the extent of the room area perceived as adequately daylit. The correlation was independent of occupant age, room function or orientation, balcony obstruction, or window size.
2. It was clear that most occupants would tolerate inadequate daylight levels in their bedroom, if they had to pick a room. The opposite is true for kitchens, as only 5 out of 108 occupants chose this room to be the underlit room of the apartment.

5 Discussion

The aim of this thesis was to provide knowledge that can be considered by policy-making agencies in their endeavours to formulate daylight performance criteria for residential spaces. Code compliance was assessed considering different urban density levels, building designs, room geometries, and evaluation criteria. In addition, the perspective of occupants was considered: the thesis analysed subjective evaluations of daylight conditions, responses regarding electric lighting use during the day, and responses regarding which rooms are prioritised in terms of daylight availability.

The results presented in the appended papers can be used to raise important points with respect to design requirements for daylight performance. While each paper discusses findings within a narrower scope, this section takes a step back to critically discuss aspects of daylight regulation based on the combined findings of all appended papers. The following sections elaborate on the following aspects: urban density and early-design considerations, daylighting multi-dwelling buildings, daylighting individual rooms, daylight performance assessments, compliance testing using European standard EN-17037, and implications of using static vs climate-based criteria.

5.1 Urban density and early-design considerations

The degree of surrounding obstructions can be intuitively understood as a negative factor when the aim is to illuminate building interiors using daylight. In this thesis, indoor daylight levels were found to be highly dependent on the degree of surrounding obstructions. Daylight levels were assessed using both “static” (Papers I & II) and “climate-based” (Paper III) daylight metrics, and in both cases, a significant correlation was found between compliance and urban density. For instance, it was shown that urban density explains approximately 64 % of the variance in development compliance rates according to the current Swedish criterion (Paper II). For a criterion using the UDI (Useful Daylight Illuminance) metric, urban density explained 68 % of the variance (Paper III). These relatively high percentages indicate that, regardless of building or apartment geometry, daylight provision for a given room is primarily dependent on the exterior environment, i.e. on how much of the celestial hemisphere is visible from the room's aperture. This key finding warrants the application of urban planning rules that can safeguard daylight levels already from the initial design stage. For instance, securing distances between buildings relative to building heights or adequate window views to the sky could function as an early design strategy. Related to this, the results of this thesis indicate that buildings erected between 1930 and 1961, which are buildings with considerable distances between them, have clearly the best performance compared to other eras of the 20th century (Paper I).

Early design massing studies could also benefit from daylight performance indicators that are calculated on the building envelope, i.e. before the interior layout of the building has been determined. Previous work has shown that daylight indicators such as the Vertical Sky Component (VSC) can be powerful predictors of building daylight performance at the urban scale (Chatzipoulka et al., 2018). A more recent and perhaps more promising predictor that accounts for both location characteristics and window size is the Sunlight Beam Index (Mardaljevic and Roy, 2017), a measure of how a window "connects" with all possible occurring sun positions, taking into consideration surrounding obstructions. In this thesis, VSC was shown to correlate strongly with compliance rates (Paper III).

Securing compliance already from an early-design stage would be crucial in the Swedish planning and building process, since many developers currently see daylight regulations as a bottleneck that arises at an advanced stage, only after they have acquired various permits and have invested significant funds in the design process. The Swedish planning and building process includes, first, the comprehensive planning, the urban and design stages, and later on during the detailed plan, the building permit, the starting permit, and the finishing permit. Daylight performance is only verified towards the building permit, and comes late in the process.

5.2 Daylighting multi-dwelling building blocks

In this thesis, the urban forms comprising multi-dwelling buildings were selected based on literature that has examined and categorised examples of Swedish architecture of the 20th century (Rådberg and Friberg, 1996).

Although construction systems and window properties have evolved since then, the archetypes of linear blocks, semi-open or closed courtyards, towers, and combinations of high-rise blocks and lower rows are still applied in today's practice. The findings of this thesis aim to provide information to the design professions regarding the benefits and caveats of different typologies in terms of daylight provision. The thesis is not focused on identifying one typology as a better choice over another one. For instance, an architectural team should not necessarily discard a closed courtyard typology, but could be aware that using high-rise courtyards (as in "post-modern reforms" typology) may necessitate larger fenestration areas, or less depth for rooms with apertures that have a limited view of the sky.

As the repetition of a specific building form creates an urban landscape, shading and self-shading for parts of a development is almost inevitable. This is particularly true when buildings are characterised by excessive height and are not spaced far enough from each other. In this thesis, semi-open courtyards were shown to perform well (Papers II, III), as they comprise lower building volumes with adequate distances between courtyard rows. However, such a typology does not serve density, i.e. it does not provide a significant number of apartments (Figure 3.13), making it less attractive for developers. In contrast, high-rise towers can provide more apartment units per stairwell and well-daylit rooms (Papers II, III), but they do not necessarily provide socially active exterior spaces, which may be an objective of the design. A combination of high-rise and low-rise buildings could be a solution to satisfy both objectives, financial and technical. Combining typologies could even be a solution on the same block, for instance on a close-courtyard block, if certain parts of the building were extruded higher and other parts were retained at a height of three storeys. This would effectively create a low-rise courtyard with point extrusions at specific locations. The low parts could allow daylight into the courtyard from the most beneficial orientation, and the high parts could provide the required density. The results presented in papers II & III along with the capacity of different typologies to house apartment units per stairwell indicate that there is room for satisfying both financial and technical objectives, provided that the right combination of typologies is chosen for a given development.

5.3 Daylighting individual rooms

Architects are faced with a plethora of requirements in order to comply with different types of regulations regarding apartment design. For instance, accessibility requirements require adequate circulation areas and specific ways of placing equipment, energy-use targets may constrain the extent of glazing areas, noise requirements may define which rooms face the street or whether an apartment will be one- or two-aspect, view considerations may drive an architect to discard an otherwise beneficial orientation in favour of a specific view, etc. Daylight requirements are only one additional set of requirements that the architect team needs to consider. Moreover, the aforementioned requirements are only a few of the requirements that can determine the apartment layout i.e. that can affect room size and position, as well as façade design. Given that additional requirements must be met, care should be taken so that any daylight-related design variable is exploited only to the extent that compliance with other requirements is not compromised. This thesis evaluated only the variables that are directly related to daylighting (Table 4.1), and pointed out which ones should be considered as primarily important during the design process. For objectives other than daylighting, other parameters may be more important.

Among the different room design variables investigated in this thesis, GFR (geometry) and VSC (urban density) were shown to affect compliance most significantly (Paper III). GFR was consistently found to relate to occupant responses regarding daylight conditions and electric lighting use (Papers IV & V). GFR was also shown to relate strongly with compliance according to different daylight metrics, both static and climate-based ones (Paper III). Therefore, it could be argued that GFR could serve as a robust proxy for daylight availability, provided that an initial assessment of surrounding obstructions has been established first, which would allow a definition of the necessary GFR minimum threshold. Deciding to grant compliance to a room that has a seemingly high GFR with no regard for surrounding obstructions is by no means wise, since VSC was shown to affect compliance substantially (Paper III). On the other hand, requesting a GFR of 10 % from every room, as is the case with the current Swedish regulations, means that rooms that have unobstructed views to the sky-dome may in fact end up with oversized windows, which in turn may lead to higher heating loads during winter and overheating during summer. Such rooms could very well achieve a $DF_P \geq 1$ % with a GFR as low as 6 %, as was revealed by simulations during this thesis; however providing adequate views out should be considered before reducing GFR for such rooms. VSC could serve as an indicator during the initial design stages, since it correlates with compliance and does not have the inherent limitations of the obstruction angle measurement of the current Swedish regulations (Paper I). The minimum required GFR ratio could be different per room in a building, based on the VSC or other façade metric obtained for each room.

In this thesis, apartments were considered as consisting of individual rooms, with easily identifiable functions per space, namely the kitchen, living room, bedroom, and dining room. The amount of daylight available for each room type was assessed using both simulations and subjective evaluations by occupants, and both methods converged to the same finding: kitchens are the darkest rooms of multi-dwelling buildings (among all rooms "occupied more than occasionally"). Bedrooms and living rooms are the next darkest rooms. Dining rooms are clearly the brightest rooms according to this research. A main reason for this is that kitchens are the preferred room to be placed deeper into the building core when there is no available façade for all rooms, whereas dining rooms are the opposite, always placed in close proximity to the façade to ensure views out. This is also related to the cost-efficiency of minimising plumbing installations when wet rooms are closer together. Placing kitchens deeper effectively makes them indirectly lit rooms, in many cases located 6 m or even further away from the window. This is unfortunate, as many people today may spend their time in the kitchen to prepare meals after returning from work, so are affected by the conditions in this room when it is still daytime.

As elaborated in Paper VI, kitchens are actually the spaces where most occupants would not tolerate poor daylight conditions, and where they use electric lighting most often during daylight hours. In addition, kitchens were reported as being underlit more often than living rooms or bedrooms. Another study investigating multi-dwelling buildings in Sweden also indicated that occupants prioritize kitchens in terms of daylight availability (Eriksson et al., 2019). The findings of this thesis and the aforementioned study are in conflict with the proposal made by the Rules Modernization Committee in December 2019 (KFMB, 2019a), which suggested that kitchens should be excluded from daylight evaluations. This decision reminds the author of a Greek proverb that is used to criticize inefficient medical practice, with a tone of irony: "If the hand hurts, cut the hand". In this author's opinion, this proposal reflects the pressure from developers to build more cost-effectively, as it would allow them to build more compact buildings, with less façade area per built volume, fewer windows, and more apartments per stairwell. Moreover, the argument that the current Swedish criteria are difficult to comply with is not supported by the findings of this thesis. When a large sample of individual rooms (n = 10888) was tested against five different daylight criteria (used in other countries or stipulated by international certification systems) the current Swedish criterion was found to be the "easiest" to comply with (Paper III).

5.4 Daylight performance assessments

When considering daylight performance of residential spaces, the primary aim is to ensure that all occupants in a building have sufficient access to daylight, which can prevent health problems arising from living in dim spaces. To define a daylight criterion for compliance testing is not a straightforward task; it requires satisfying a range of parameters.

Firstly, there is a necessity for a daylight metric that accounts for parameters affecting our appreciation of daylight in the built environment. For instance, daylight factors do not consider the diurnal sun path that varies with season, nor the amount of sunshine or cloudiness in a particular location. If these parameters are important, i.e. if they affect our appreciation of indoor daylight conditions and our behaviour in our dwellings, then daylight factors must be ruled out in favour of more complex daylight metrics.

Secondly, there is a necessity to create a pass-or-fail condition, i.e. a demarcation on the metric scale that determines whether a room (or other space) passes or qualifies. Demarking the scale on a specific threshold value should be based on scientific research showing what light conditions are proven to provide a healthy environment and to satisfy occupants.

Thirdly, there is a necessity for simplicity, i.e. a necessity for a criterion to be clear, testable in a reasonable time, and not difficult to use by all relevant parties in the design process. Practitioners of architecture and consultants need to be trained and familiar with the respective software tools and methods prescribed by a standard, but the standard itself and its criteria need to be sufficiently simple and straightforward to ensure that they do not complicate and delay the design process.

Fourthly, there is a necessity to satisfy state and private stakeholders that depend on the financial feasibility of residential projects. A government or municipality may be faced with having to satisfy a large housing demand (as is the case today), while developers may find it hard to build cost-effectively if they cannot accommodate sufficient apartments within a given plot. Therefore, adopting an unreasonably high value on a metric scale may result in unrealistic and unfeasible targets and thereby distort the building process.

According to Paper I, the current Swedish regulation includes criteria with inherent limitations. The findings of this thesis suggest that two compliance testing methods could be considered as possible alternatives: 1) a combination of VSC and GFR assessments, and 2) a UDI assessment. Both alternatives account for surrounding obstructions, which were found to affect compliance substantially. The first alternative has the benefit of being simpler, and could supersede the current GFR-method. The VSC calculation could come at an early design stage, when the interior layout of an apartment has not yet been decided. The second alternative can take climate and orientation into account, as well as overheating issues, and could supersede the current point daylight factor criterion (DF_P). Since it incorporates a climate-based metric, it can take orientation into account, which was shown to affect occupant behaviour in terms of electric lighting use (Paper V). On the negative side, it is more complicated in terms of the simulation method required, but it can be argued that practitioners in the future will be able to adopt to more complex methods if given appropriate training on the matter.

Target values for each criterion alternative is a subject for future research, where occupant evaluations would need to be compared to photometric measurements; this was not possible in this research. The extent of such target values would also need to factor financial aspects and more components of building regulations. The author thinks that the current situation in the building industry is characterised by pressure to deregulate the construction process. In this thesis, the current Swedish criterion was shown to be the easiest to comply with among all other criteria tested (Paper III), but still, developers have expressed their concerns and have found it to be a bottleneck in their projects. A minimum window size or illuminance that seems low for academics could in fact seem high for other stakeholders.

5.5 Using EN-17037 for compliance testing

If there were a shortlist of international researchers who have dedicated a considerable proportion of their work to finding meaningful daylight performance and compliance criteria, then the list would include J. Mardaljevic, who provided the rationale for the current European standard EN-17037 along with J. Christoffersen (Mardaljevic and Christoffersen, 2017). Despite that, J. Mardaljevic has reiterated what is clearly stated in standard EN-17037, which is that the daylight factor and illuminance thresholds in it were not meant to be compliance targets, but rather recommendations for good daylight design practice (Mardaljevic, 2020).

There is no doubt that standard EN-17037 is methodologically more advanced compared to the current Swedish regulation. However, it should be noted that compliance verification is about testing whether a design exceeds a minimum level of illumination, not an ideal level of illumination. The author has received feedback on this research by architects who claimed that it is better to exclude kitchens from evaluations and follow

EN-17037 for all other rooms. Compared to the current Swedish criterion, complying with the daylight factor criterion of EN-17037 requires nearly 2.5 times higher illuminance levels, which has severe consequences on room daylight compliance as presented in Paper III of this thesis. The difficulty in complying with EN-17037 speaks volumes about the bottleneck it would create in the construction process if it were to become a mandatory requirement. In addition, the results presented in Paper III indicate that a room must be shallow and have a large glazing area in order to comply with the daylight factor criterion of EN-17037. Previous work has also pointed out that complying with EN-17037 leads to oversized glazing areas, and an overall increase of the building energy use (Bernard and Flourentzos, 2019).

5.6 Static vs climate-based criteria

The disagreement between the two EN-17037 calculation methods presented in Paper III is a good example of the difference between static and climate-based metrics. The two methods use the same set of assumptions, except for sky conditions. The "illuminance levels" method (EN17037-IL) was clearly shown to yield higher compliance rates compared to the "daylight factor" method (EN7037-DF). This indicates that a climate-based assessment can reveal the potential of a dwelling to be daylit more precisely than a daylight factor approach can predict. The significant disagreement between the two methods also indicates that the daylight factor method of EN-17037 was perhaps a halfway measure intended to be superseded by the climate-based method. A climate-based daylight metric can predict whether a room is sufficiently daylit due to its orientation. Orientation was shown to dictate daytime electric lighting use in dwellings (Paper V), which in turn was shown to be strongly associated with daylight availability (Paper VI). Climate-based metrics also account for the varying luminance of different sky parts throughout the day and seasons. In this thesis, the exterior circulation typologies ranked higher among typologies when tested with climate-based criteria instead of daylight factor-based criteria. The latter shows that climate-based criteria can capture the ability of these buildings to exploit light entering from below the exterior circulation corridors, at times when the sun is low enough or the sky is bright enough close to the horizon.

6 Conclusions

This research focused on the state of compliance of multi-dwelling buildings, the factors affecting compliance, and how different criteria affect the degree of compliance. Occupant responses were also investigated, to assess the importance of daylighting dwellings, and to highlight key aspects that should be considered when devising daylight evaluation criteria.

One important conclusion is that urban densification significantly affects daylight availability in multi-dwelling buildings, which highlights the importance of applying early design evaluation criteria, perhaps at the urban scale, i.e. before a building design is completely determined. Since urban densification is ongoing in Sweden and elsewhere, formulating such criteria is imperative. These criteria also need to be expressed as "mandatory provisions" instead of "general recommendations", which was the case in the last quarter of the 20th century. The results show that buildings constructed during this period significantly underperformed in terms of daylight availability compared to their predecessors.

This thesis also emphasises the need to modernise current regulations. The problem connected to the alternative pathways for compliance (area- or daylight factor-based) and the fact that it is easier to comply with one compared to the other implies that practitioners may engage in deliberate game-playing to select how to assess a space to give the most optimistic result.

Constraints on the form and size of residential developments are necessary if all rooms are to be provided with adequate natural light. Typologies with heavily shaded apertures were shown to admit consistently less daylight, regardless of the criterion used in the assessment. In contrast, rooms with a larger sky exposure angle and a higher glass-to-floor ratio were found to be more often compliant. Guidelines could vary between room types, as there seems to be a high level of agreement among occupants regarding which rooms are prioritised over others in terms of daylight availability.

Apart from previously published health benefits of daylight, motivation to strengthen daylight regulations could also rely on the potential to reduce unnecessary electricity use for lighting. Although lighting is not the main cause of electricity use in dwellings, it can be expected to increase in the future if we consider the anticipated trends in remote working, which are facilitated by today's IT technology, as shown during the Covid-19 pandemic. If the risk of increased electricity for lighting is to be minimised, daylight design measures and criteria for residential spaces are needed.

Climate-based criteria, i.e. criteria that consider the hourly daylight availability from the sun and sky could be considered in future regulations. Orientation was shown to significantly affect electric lighting use according to occupant responses, which indicates that future daylight assessments should account for all different hours of the day, i.e. for the effect of the sun path relative to the building facade. A pronounced difference between climate-based and daylight factor-based assessments was revealed when the two daylight criteria of standard EN-17037 were compared, the climate-based and the daylight factor-based criterion. The fact that the climate-based criterion yielded higher compliance indicates that a more accurate representation of sky conditions, on an hourly basis, can reveal a different potential of a design to admit daylight, in particular a higher potential.

Regardless of the technical aspects considered in order to formulate a given daylight evaluation criterion, its acceptance by the building industry will still depend on its flexibility and its potential to allow for economic profitability of future real estate investments. Although it is easier to comply with the current Swedish criteria compared to other criteria examined in this thesis, the difficulty in meeting daylight requirements in new constructions has already been voiced, and a proposal to exclude kitchens from evaluations has been filed; the latter contradicts the findings of this research as, according to the presented survey results, a dark kitchen would be tolerated by very few occupants. In devising daylight criteria, the technical choices may be suggested following scientific research, but the final (and ethical) choice regarding which spaces must be illuminated and to what degree lies with the policymaking institutions.

7 Future work

The suitability of the presented UDI criterion for compliance assessments could be further researched/investigated. The survey results indicate that the semantic differential scales used to collect responses on space brightness are reliable. Comparing occupant responses with UDI levels derived from in-situ illuminance measurements could be considered for future research, to verify that the criterion outcome is in agreement with occupant judgements of daylight conditions.

New rules-of-thumb could be developed to derive compliance predictions using only façade measurements. The two variables that most substantially affect compliance, namely Glass-to-Floor Ratio and Vertical Sky Component, could be embedded in a simplified formula to predict compliance requirements, e.g. a maximum allowed room depth, to guide early-design decision making. Such an approach could also consider metrics similar to the Sunlight Beam Index, which accounts for building orientation and window size, two variables that are not considered by the Vertical Sky Component.

Spatial characteristics of residential architecture could be considered in early-design compliance predictions. As was identified across the buildings investigated in this thesis, approximately 60-65 % of the building plan layout consists of functions requiring daylight in most building typologies. Overall building dimensions (depth and width) could be associated with the apartment plan layouts produced, e.g. probable room depths and positioning, to derive the location of the daylight-requiring areas across the building plan. Subsequently, the required façade openings needed to adequately illuminate these areas could be calculated based on rules-of-thumb or simplified equations.

Future research could benefit from the data collected during this research. An extensive amount of room geometry and surface reflectance values were collected as part of the methodological requirements of this thesis. In Paper I, the reader can find typical dimensions of residential spaces, which can be used as reasonable assumptions for early-design and simulation input data. Paper IV presents measured light reflectance values for walls, floors and ceilings that are relative to apartment spaces.

It is the author's humble hope that the knowledge provided by this doctoral thesis will contribute to policymaking and design guidelines relating to daylight performance criteria for residential spaces. Overall, this thesis emphasises the importance of daylighting for dwellings and the need for clear and reliable early design assessment criteria, as well as simplified equations at the urban scale to ensure that urban densification does not result in diminished environmental quality for urban dwellers.

Summary

This thesis focuses on the daylight performance of Swedish apartment blocks. It presents the parameters affecting indoor daylight levels, it assesses whether daylight provision is adequately regulated, and it examines occupants' responses regarding daylight conditions in their dwellings. As a result, the work presented in this thesis contributes to knowledge supporting the development of more appropriate daylight criteria for residential spaces, that could be considered by policy makers in their endeavours to upgrade building regulations.

The main outcomes of this thesis can be summarised under three main themes: 1) limitations of current daylight criteria in Swedish building regulations, 2) determinants of daylight compliance and considerations for future regulations, and 3) inhabitants' response regarding daylighting and electric lighting use in apartments.

Limitations of current daylight criteria in Swedish building regulations

The formulation of the current two daylight criteria in the building code is not optimal because of three limitations: 1) the way to assess daylight is not clearly defined for all types of spaces, 2) surrounding buildings that may shade are not always considered, and 3) sun position is not considered.

Another consideration relates to the regulatory hierarchy characterizing the building code. In Sweden, some parts of the building code are mandatory requirements, while other parts, including quantified daylight criteria, are only stated as general recommendations, which are not legally binding per se. Ironically, of the buildings evaluated in this thesis, the ones erected following the introduction of quantified daylight criteria in 1975 were shown to perform worse than the ones erected prior to that year. This is an indication that quantified daylight criteria need to be stated as mandatory requirements if they are to be followed, similarly to how current energy compliance criteria are stated today.

Determinants of daylight compliance and considerations for future regulations

Densifying the built environment was shown to block daylight regardless of apartment design, which indicates that daylight provision is primarily dependent on the exterior environment. This observation leads to the proposal of instigating early-design compliance testing criteria at the urban scale. Among different characteristics of residential rooms, the amount of façade glazing relative to floor area, and the amount of sky visible from windows were shown to be the most influential parameters of indoor daylight levels.

The importance of criterion choice in order to judge whether spaces are adequately daylit or not was also assessed. The current Swedish criterion was found to be the easiest to comply with compared to other criteria. A shift to a more advanced daylight criterion could consider using the Useful Daylight Illuminance (UDI) metric, which is superior to the current regulation as it accounts for orientation and sunlight, and can be used in tandem with thermal comfort evaluations. Significant compliance similarities were found between the current criterion and a UDI-based criterion.

Inhabitants’ response regarding daylighting and electric lighting use

Three important considerations can be summarized following a survey on daylight conditions of apartments. Firstly, higher levels of daylight are associated with less frequent electric lighting use. Secondly, room orientation is a key factor in reducing electric lighting use. Occupants reported less daytime lighting use in west-facing rooms, which can be attributed to residential occupancy patterns, i.e., people returning home when the sun is due west. This finding illustrates the need for daylight criteria that account for sun position. Thirdly, it seems that there is an agreement among occupants on which rooms are prioritized in terms of daylight. The majority of respondents selected the bedroom as the room they would tolerate underlit if they had to pick a room. On the other hand, very few occupants would choose to have their kitchen or living room as the darkest room of their apartment. This information could be considered in future regulations that wish to differentiate between room types.

Overall, this thesis demonstrates the importance of urban planning for daylighting, the implications of using different designs on daylight availability, the need for proper well-formulated regulations and a rigorous compliance path, the connection between daylight availability and electric lighting use, and the fact that occupants have specific preferences regarding the illumination of their apartments.

Sammanfattning

Denna avhandling fokuserar på dagsljusprestanda för svenska flerbostadshus. Den presenterar parametrarna som påverkar dagsljusnivåerna inomhus, den utvärderar om dagsljusförsörjning är tillräckligt reglerad och den undersöker boendes svar avseende dagsljusförhållanden i deras bostäder. Arbetet som presenteras i avhandlingen bidrar med kunskap och stöd för utveckling av mer lämpliga dagsljuskriterier för bostadsutrymmen, som politiker och andra beslutsfattare kan överväga i deras strävan att förbättra byggregler.

Avhandlingens huvudsakliga resultat kan sammanfattas i tre huvudteman; 1) begränsningar i gällande svenska byggreglers kriterier för dagsljus, 2) bestämmande faktorer för att uppfylla byggregler för dagsljus och överväganden för framtida förordningar och 3) boendes svar avseende dagsljus och användning av elektrisk belysning.

Begränsningar i gällande svenska byggreglers kriterier för dagsljus

Formuleringen av de gällande två dagsljuskriterierna i byggregler är inte optimal på grund av tre begränsningar: 1) sättet att utvärdera dagsljus är inte klart definierat för alla typer av utrymmen, 2) omgivande byggnaders skugga beaktas inte alltid, och 3) solens position beaktas inte.

En annat övervägande är kopplat till den regulatoriska hierarkin som kännetecknar bygglagen. I Sverige är vissa delar av bygglagen obligatoriska, medan andra delar, inklusive kvantifierade dagsljuskriterier, endast anges som allmänna rekommendationer som inte är juridiskt bindande. Vid utvärderingen av byggnaderna i denna avhandling framkom ironiskt nog att byggnaderna som uppförts efter införandet av kvantifierade dagsljuskriterier 1975 hade sämre resultat än de som byggts dessförinnan. Detta är en indikation på att kriterierna för kvantifierat dagsljus måste vara obligatoriska krav om de ska följas, på samma sätt som kraven avseende energi är utformade i nuläget.

Bestämmande faktorer för att uppfylla byggregler för dagsljus och överväganden för framtida förordningar

Förtätning i den byggda miljön visade sig blockera dagsljus oberoende av lägenhetens design, vilket indikerar att dagsljusförsörjningen i första hand är beroende av den yttre miljön. Denna iakttagelse föranleder förslaget att ha testningskriterier i ett tidigt designskede på stadsnivå. Bland de olika egenskaperna hos bostadsrum visade sig mängden fönsteryta i fasaden i förhållande till golvyta och mängden himmel som är synlig från fönster vara de mest inflytelserika parametrarna för dagsljusnivåer inomhus.

Betydelsen av utvalda kriterier för att utvärdera om utrymmen har tillräckligt dagsljus eller inte bedömdes också. Det nuvarande svenska kriteriet visade sig vara det enklaste att uppfylla jämfört med andra kriterier. Vid en övergång till ett mer avancerat dagljuskriterium kan metoden UDI (Useful Daylight Illuminance) övervägas. Metoden är överlägsen nuvarande reglering eftersom den även tar hänsyn till byggnadens riktning och solljus samt kan användas tillsammans med utvärderingar av värmekomfort. Betydelsefulla likheter återfanns mellan det nuvarande kriteriet och ett UDI-baserat kriterium.

Boendes svar avseende dagsljus och användning av elektrisk belysning

Tre viktiga överväganden framkom och kan sammanfattas efter en undersökning om lägenheters dagsljus. För det första är högre nivåer av dagsljus förknippade med mindre frekvent användning av elektrisk belysning. För det andra är rummens riktning en nyckelfaktor för att minska användningen av elektrisk belysning. Boende rapporterade mindre användning dagtid av belysning i rum som vetter mot väster, vilket kan förklaras av boendes användningsmönster dvs.

människor återvänder hem när solen står i väster. Detta resultat illustrerar behovet av dagsljuskriterier som tar hänsyn till solens läge. För det tredje verkar det som om boende är överens om vilka rum som prioriteras när det gäller dagsljus. Majoriteten av de tillfrågade valde sovrummet som det rum de främst skulle tolerera som underbelyst. Däremot skulle mycket få boende välja att ha kök eller vardagsrum som det mörkaste rummet i lägenheten. Denna information kan beaktas vid framtida reglering som önskar skilja mellan rumstyper.

Sammantaget demonstrerar denna avhandling vikten av stadsplanering för dagsljus, konsekvenserna av att använda olika design för tillgängligheten av dagsljus, behovet av korrekt och välformulerad reglering samt noggrann plan kring efterlevnads granskning, sambandet mellan tillgängligt dagsljus och användning av elektrisk belysning, samt att boende har specifika preferenser när det gäller upplysning av deras lägenheter.

References

Aizlewood M, Laforgue P, Mittanchey R, Carroll W, Hitchcock R. (1998). *Data sets for the validation of daylighting computer programs:* Proceedings of the Daylighting'98 Conference. Paper presented at the International Conference on Daylighting Technologies and Energy Efficiency in Buildings.

Andersson L, Engström P, Lindén A. (1971). *Attitudes to blocks of flats with balcony access.* National Swedish Building Research Summaries, R42:1971.

Bernard P, Flourentzos F. (2019). Perspective on daylight provision according to the new European standard "Daylight in Buildings" (EN 17037). *Journal of Physics: Conference Series. 1343(1): 1.*

Björk C, Reppen L, Kallstenius P. (2013). *Så byggdes husen 1880-2000* : arkitektur, konstruktion och material i våra flerbostadshus under 120 år (In English: This is how the houses were built 1880 - 2000: architecture, construction and materials in our multi-dwelling buildings for 120 years) (sixth edition). Västerås: Formas.

Boubekri M. (2008). *Daylighting, Architecture and Health: Building Design Strategies* (first edition). Oxford: Architectural Press.

Bournas I. (2020a). Daylight compliance of residential spaces: Comparison of different performance criteria and association with room geometry and urban density. *Building and Environment. 185: 107276.* doi:https://doi.org/10.1016/j.buildenv.2020.107276.

Bournas I. (2020b). *Daylight in Swedish multi-dwelling buildings:* Research on the effects of urban densification, building typology and occupant behavior. Center for Housing Architecture, Form Design Center. Retrieved from https://www.chalmers.se/SiteCollectionDocuments/Centrum/CBA/Nyheter/2020/LTH4-Iason_Bournas.pdf. Last accessed: February 26, 2020.

Bournas I. (2021). Swedish daylight regulation throughout the 20th century and considerations regarding current assessment methods for residential spaces. *Building and Environment. 191: 107594.* doi:https://doi.org/10.1016/j.buildenv.2021.107594.

Bournas I, Dubois M-C. (2019). Daylight regulation compliance of existing multi-family apartment blocks in Sweden. *Building and Environment. 150: 254-265.* doi:https://doi.org/10.1016/j.buildenv.2019.01.013.

BOVERKET. (1988). *BFS 1988:18 - Nybyggnads regler* (English: New building regulations). Stockholm (SE): The National Board of Housing, Building and Planning.

BOVERKET. (1993). *BFS 1993:57*. Stockholm (SE): The National Board of Housing, Building and Planning.

BOVERKET. (2014). *BFS 2014:3*. Stockholm (SE): The National Board of Housing, Building and Planning.

BOVERKET. (2020a). *Byggregler – en historisk översikt från BABS till BBR* (English: Building rules - a historical overview from BABS to BBR). Retrieved from https://www.boverket.se/sv/byggande/uppdrag/avslutade-uppdrag/oversyn-av-boverkets-byggregler/byggregler--en-historisk-oversikt/. Last accessed: September 23, 2020.

BOVERKET. (2020b). *Mandatory provisions and general recommendations BFS 2011:6 with amendments up to BFS 2018:4*. Karlskrona (Sweden): The Swedish National Board of Housing, Building and Planning.

BOVERKET. (2020c). *National Board of Housing, Building and Planning*. Retrieved from https://www.boverket.se/en/start/about/about-boverket/. Last accessed: September 23, 2020.

BOVERKET. (2020d). *Regulatory hierarchy - from law to general recommendation*. Retrieved from https://www.boverket.se/en/start/building-in-sweden/swedish-market/laws-and-regulations/national-regulations/regulatory-hierarchy/. Last accessed: September 23 2020.

BOVERKET. (2020e). *The Swedish National Board of Housing, Building and Planning - About Boverket*. https://www.boverket.se/en/start/about/about-boverket/. Last accessed: December 26, 2020.

BS. (1874). *Byggnads-stadga och Brands-stadga för rikets städer* (In English: Building Charter and Fire Charter for the cities of the kingdom). Retrieved from https://www.boverket.se/contentassets/22140678c50841128f99d542d6ab2eb7/1874-byggnadsstadga-brandstadga.pdf. Last accessed: December 20, 2020.

CEN. (2018a). European Standard EN 12665:2018 *Light and lighting - Basic terms and criteria for specifying lighting requirements*. Brussels (Belgium): European Committee for Standardization.

CEN. (2018b). European Standard EN 17037:2018 *Daylight in Buildings*. Brussels (Belgium): European Committee for Standardization.

Chatzipoulka C, Compagnon R, Kaempf J. (2018). An image-based method to evaluate solar and daylight potential in urban areas Proceedings of the Symposium on Simulation for Architecture and Urban Design: *Society for Computer Simulation International. p. 1-8*.

CIE. (2004). *Spatial Distribution of Daylight* - CIE Standard General Sky. International Commission on Illumination.

Dufton AF. (1946). *Protractors for the Computation of Daylight Factors* (Vol. H. M. Stationery Office). London, UK.

Eriksson S, Waldenström L, Tillberg M, Österbring M, Kalagasidis AS. (2019). Numerical simulations and empirical data for the evaluation of daylight factors in existing buildings in Sweden. *Energies. 12(11)*: 2200. doi:https://doi.org/10.3390%2Fen12112200.

Fritzell B, Löfberg HA, Statens institut för b. (1970). *Dagsljus inomhus*: Statens institut för byggnadsforskning.

Goral CM, Torrance KE, Greenberg DP, Battaile B. (1984). Modeling the interaction of light between diffuse surfaces. *SIGGRAPH Comput. Graph. 18(3): 213-222*. doi:10.1145/964965.808601.

Hall T, Rörby M. (2009). Stockholm: *The Making of a Metropolis* (first edition). Taylor & Francis e-Library: Routledge.

Hall T, Vidén S. (2005). The Million Homes Programme: a review of the great Swedish planning project. *Planning Perspectives. 20(3): 301-328*. doi:1080/02665430500130233.

Hopkinson RG. (1963). *Architectural physics: lighting*. London: H.M. Stationery Office.

IES. (2012). LM-83-12, Spatial daylight autonomy (sDA) and annual sunlight exposure (ASE). New York, US: *Illuminating Engineering Society*.

Jacobs A. (2014). Getting the measure of daylight - the climate sceptic. *The Lighting Journal: 15 - 17*.

Jarvis D, Donn M. (1997). *Comparison of computer and model simulations of a daylit interior with reality*. Paper presented at the IIBPSA / Building Simulation 1997, Prague, Czech Republic.

Jensen HW. (1996). *Global illumination using photon maps*. Paper presented at the Proceedings of the eurographics workshop on Rendering techniques '96. Porto, Portugal.

Julian W. (1998, May 11-13). *Daylighting standards, codes and policies*. Paper presented at the International Conference on Daylighting Technologies for Energy Efficiency in Building, Ottawa, Canada.

Kajiya JT. (1986). The rendering equation. *SIGGRAPH Comput. Graph. 20(4): 143-150*. doi:10.1145/15886.15902.

KBS. (1960). *BABS 1960 - Anvisningar till byggnadsstadgan* (English: Intructions for building regulations). Karlskrona (Sweden): Royal Building Board.

KFMB. (2019a). *The Building Rules Modernisation Committee,* Våra förslag - Slutbetänkande: Modernare byggregler – förutsägbart, flexibelt och förenklat (English: Our proposal - Final report: More modern building rules - predictable, flexible and simplified). Retrieved from http://modernarebyggregler.se/vara-forslag/

KFMB. (2019b). *Modernare byggregler – förutsägbart, flexibelt och förenklat* (English: More modern building rules - predictable, flexible and simplified). Retrieved from https://news.cision.com/se/kommitten-for-modernare-byggregler/r/forslag-pa-modernare-byggregler-lamnas-till-regeringen,c2994845. Last accessed: September 16, 2020.

Küller R, Wetterberg L. (1993). Melatonin, cortisol, EEG, ECG and subjective comfort in healthy humans: Impact of two fluorescent lamp types at two light intensities. *Lighting Research & Technology. 25(2): 71*.

Küller R, Wetterberg L. (1996). The subterranean work environment: impact on well-being and health. *Environment International. 22(1): 33*.

Kunkel S, Kontonasiou E, Arcipowska A, Mariottini F, Atanasiou B. (2015). *Indoor Air Quality, Thermal Comfort and Daylight - analysis of residential building regulations in eight EU member states*. Retrieved from

Länsstyrelsen i Stockholms l. (2004). *Hej bostad : om bostadsbyggande i Storstockholm 1961-1975*: Länsstyrelsen i Stockholms län.

Legnér M, Leijonhufvud G, Tunefalk M. (2020). Energy policy and conservation planning in Sweden: a longitudinal evaluation. International *Journal of Building Pathology and Adaptation. 38(4): 555-572*. doi:10.1108/IJBPA-11-2019-0096.

Malmö-Stad. (2020a). *Stadsatlas*. Retrieved from https://kartor.malmo.se/rest/leaf/1.0/?config=../configs-1.0/malmo_atlas.js. Last accessed: December 14, 2020.

Malmö-Stad. (2020b). *Stadsbyggnadskontorets arkiv* [Municipal building archives]. Malmö (Sweden): Malmö Stad. Retrieved from https://malmo.se/Service/Bygga-och-bo/Stadsbyggnadskontorets-arkiv.html. Last accessed: May 7, 2020.

Mardaljevic J. (1995). Validation of a lighting simulation program under real sky conditions. *Lighting Research & Technology. 27(4): 181*.

Mardaljevic J. (2013). Rethinking daylighting and compliance. *Journal of Sustainable Design & Applied Research. 1(3): Article 1*.

Mardaljevic J. (2015, April 16 - 17). *Climate-Based Daylight Modelling And Its Discontents*. Paper presented at the CIBSE Technical Symposium, London (UK).

Mardaljevic J. (2020). New thinking on daylight/sunlight links planning and performance. *Daylighting, 12-16*.

Mardaljevic J, Andersen M, Roy N, Christoffersen J. (2012). *Daylighting Metrics: Is there a relation between Useful Daylight Illuminance and Daylight Glare Probabilty?* Paper presented at the Building Simulation and Optimization Conference BSO12. Loughborough, UK. http://infoscience.epfl.ch/record/179939/files/2012_Mardaljevical%20BSO2012%20UDI-DGPsComp_FINAL.pdf

Mardaljevic J, Christoffersen J. (2017). 'Climate connectivity' in the daylight factor basis of building standards. *Building and Environment. 113: 200-209*. doi:10.1016/j.buildenv.2016.08.009.

Mardaljevic J, Heschong L, Lee E. (2009). Daylight metrics and energy savings. *Lighting Research & Technology. 41(3): 261-283*. doi:10.1177/1477153509339703.

Mardaljevic J, Roy N. (2017). *Envelope first / Inside later*: Aperture sunlight and skylight indices.

Marsh R. (2017). On the modern history of passive solar architecture: exploring the paradox of Nordic environmental design. *The Journal of Architecture. 22(2): 225-251*. doi:10.1080/13602365.2017.1298652.

Nabil A, Mardaljevic J. (2005). Useful daylight illuminance: a new paradigm for assessing daylight in buildings. *Lighting Research & Technology. 37(1): 41-57*. doi:10.1191/1365782805li128oa.

OMNI. (2016). *Boverket: 700000 new homes must be built*. Retrieved from https://omni.se/boverket-700-000-nya-bostader-maste-byggas/a/1k9B. Last accessed: September 10.

Perez R, Seals R, Michalsky J. (1993). Article: All-weather model for sky luminance distribution—Preliminary configuration and validation. *Solar Energy. 50: 235-245*. doi:10.1016/0038-092X(93)90017-I.

Rådberg J, Friberg A. (1996). *Svenska stadstyper : historik, exempel, klassificering* (In English: Swedish city types: history, examples, classification) (first edition). Stockholm (Sweden): Kungliga Tekniska Högsklolan Stockholm.

Regeringskansliet. (2019). Ministry of Finance, Modern building rules - predictable, flexible and simplified - *SOU 2019: 68*. Retrieved from https://www.regeringen.se/rattsliga-dokument/statens-offentliga-utredningar/2019/12/sou-201968/. Last accessed: December 7 2020.

Reinhart C. (2011). *Daylight Performance Predictions*. In Hensen JLM & Lamberts R (editors). Building Performance Simulation for Design and Operation. NY, USA: Spon Press.

Reinhart CF. (2001). *Daylight availability and manual lighting control in office buildings - simulation studies and analysis of measurement*. (PhD). University of Karlsruhe.

Reinhart CF, Mardaljevic J, Rogers Z. (2006). Dynamic Daylight Performance Metrics for *Sustainable Building Design. LEUKOS. 3(1): 7-31*. doi:10.1582/LEUKOS.2006.03.01.001.

Rogers P, Dubois M-C, Tillberg M, Österbring M, Alenius M, Bournas I, Larsson A, Lundgren M, Söderlund M, Vakouli V. (2018). *Moderniserad dagsljusstandard* (English: Modernized daylight standard). Retrieved from SBUF ID: 13209, http://www.bau.se/wp-content/uploads/2018/12/SBUF-13209-Slutrapport-Moderniserad-dagsljus-standard.pdf:

Sadeghipour Roudsari M, Pak M. (2013). *Ladybug: a parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design*. Paper presented at the Proceedings of the 13th International IBPSA Conference Held in Lyon. France

Sadeghipour Roudsari M, Subramaniam S. (2016). *Automating Radiance workflows with Python*. Paper presented at the The 15th Annual Radiance Workshop. Padua, Italy. https://www.radiance-online.org/community/workshops/2016-padua/presentations/213-Sadeghipour-Subramaniam-AutomatingWorkflows.pdf

SBUF. (2017). Swedish construction industry development fund - *FLER, BILLIGARE OCH BÄTTRE BOSTÄDER* – Är det möjligt genom att förenkla byggreglerna? (In English: More, cheaper and better housing. Is it possible by simplifying the building regulations?). https://www.boverket.se/contentassets/1335ce31e45a4c7a9b3c78dec999d594/sbuf-13271-fler-billigare-och-battre-bostader.pdf. Last accessed.

SCB. (2019a). *Dwelling stock 31/12/2019*. Retrieved from https://www.scb.se/en/finding-statistics/statistics-by-subject-area/housing-construction-and-building/housing-construction-and-conversion/dwelling-stock/. Last accessed: February 6, 2020.

SCB. (2019b). Statistics Sweden - *Completed dwellings and number of rooms including kitchen in newly constructed buildings by region and type of building, Year 1975 - 2018*. Retrieved from http://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__BO__BO0101__BO0101A/LghReHustypAr/. Last accessed: September 16, 2020.

SCB. (2019c). Statistics Sweden - *Dwelling stock 31/12/2019*. Retrieved from https://www.scb.se/en/finding-statistics/statistics-by-subject-area/housing-construction-and-building/housing-construction-and-conversion/dwelling-stock/. Last accessed: February 6, 2020.

SCB. (2019d). Statistics Sweden - *Markanvändningen i Sverige* (In English: Land use in Sweden), 7th edition.: Statistics Sweden Retrieved from https://www.scb.se/contentassets/eaa00bda68634c1dbdec1bb4f6705557/mi0803_2015a01_br_mi03br1901.pdf.

SCB. (2019e). Statistics Sweden - *Population within and outside of localities/urban areas 1800-2018*. Retrieved from https://www.scb.se/en/finding-statistics/statistics-by-subject-area/environment/land-use/localities-and-urban-areas/pong/tables-and-graphs/population-within-and-outside-of-localitiesurban-areas/. Last accessed: December 15, 2020.

SCB. (2019f). Statistics Sweden - *There are 8.9 million inhabitants in urban areas*. https://www.scb.se/en/finding-statistics/statistics-by-subject-area/environment/land-use/localities-and-urban-areas/pong/statistical-news/localities-and-urban-areas-2018/. Last accessed: December 20, 2020.

SCB. (2020a). *Localities and urban areas* (Finding statistics / Environment / Land use / Localities and urban areas). Retrieved from https://www.scb.se/en/finding-statistics/statistics-by-subject-area/environment/land-use/localities-and-urban-areas/. Last accessed: December 15, 2020.

SCB. (2020b). Statistics Sweden - *Completed dwellings and number of rooms including kitchen in newly constructed buildings by region and type of building. Year 1975 - 2019*. https://www.statistikdatabasen.scb.se/px-web/en/ssd/START__BO__BO0101__BO0101A/LghReHustypAr/. Last accessed: December 11, 2020.

SCB. (2020c). Statistics Sweden - *Densification in half of Sweden's urban areas*. https://www.scb.se/en/finding-statistics/statistics-by-subject-area/environment/land-use/localities-and-urban-areas/pong/statistical-news/localities-and-urban-areas-2018-population-2019/. Last accessed: December 18, 2020.

SCB. (2020d). Statistics Sweden - *Low population growth in Sweden during the coronavirus pandemic, 2020*. https://www.scb.se/en/finding-statistics/statistics-by-subject-area/population/population-composition/population-statistics/pong/statistical-news/population-statistics-januaryjune-2020/. Last accessed: December 2, 2020.

SCB. (2020e). Statistics Sweden - *Sweden's population grew by a million in the last ten years*. https://www.scb.se/en/finding-statistics/statistics-by-subject-area/population/population-composition/population-statistics/pong/statistical-news/swedens-population-2019--population-changes/. Last accessed: December 2, 2020.

SCB. (2020f). *Statistics Sweden*. https://www.scb.se/en/. Last accessed: December 7, 2020.

SFS. (1931). *Stadsplanelag SFS 1931:142* (English: City planning law SFS 1931:142). Retrieved from https://www.boverket.se/contentassets/22140678c50841128f99d542d6ab2eb7/1931-stadsplanelag.pdf. Last accessed: September 6, 2020.

SIS. (1988). Swedish Standard SS 914201 - *Building design - Daylighting - Simplified method for checking required window glass area*. Swedish Institute for Standards.

SP. (1967). *SBN 67 - Svensk Byggnorm 67* (English: Swedish building standard). Stockholm (SE): Statens Planverk (English: The National Planning Agency).

SP. (1975). *SBN 1975 - Svensk byggnorm* (English: Swedish building standard). Stockholm (SE): Statens planverk (English: The National Planning Agency).

SP. (1980a). *Kommentarer till Svensk Byggnorm* (English: Comments on Swedish building standard). Stockholm (SE): Statens planverks (English: The National Planning Agency).

SP. (1980b). *SBN 1980 - Svensk byggnorm* (English: Swedish building standard). Stockholm (SE): Statens planverks (English: The National Planning Agency).

Stockholm stad, *Bygg och plantjänsten* (In English: Stockholm city, Construction and planning service). (2018). Retrieved from http://insynsbk.stockholm.se/Byggochplantjansten/Startsida-ny/. Last accessed: December 3, 2020.

Subramaniam S, Mistrick R. (2017). *A more accurate approach for calculating illuminance with daylight coefficients*. Paper presented at the The IES Annual Conference 2017. Portland, Oregon, USA.

Tregenza P. (2014). Opinion: Climate-based daylight modelling or daylight factor? *Lighting Research & Technology. 46(6): 618-618*. doi:10.1177/1477153514557602.

Tregenza P, Mardaljevic J. (2018). Daylighting buildings: Standards and the needs of the designer. *Lighting Research & Technology. 50(1): 63-79*. doi:10.1177/1477153517740611.

Tregenza P, Wilson M. (2011). *Daylighting*: Architecture and Lighting Design: Routledge

Ubbelohde MS, Humann C. (1998). *Comparative evaluation of four daylighting software programs*. Proceedings of ACEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA: 23-28.

Ward GL, Shakespeare S. (1998). *Rendering with radiance: the art and science of lighting visualization*: Morgan Kaufmann Publishers Inc.

Whitted T, Foley JD. (1980). An Improved Illumination Model for Shaded Display. *Communications of the ACM. 23(6): 343-349*. doi:10.1145/358876.358882.

Errata

This errata sheet lists errors and their corrections for the six appended articles (Papers I – VI) of this thesis.

Location	**Error**	**Correction**
Paper II, page 259, section 3.1, second paragraph	The corresponding building code is shown in red to highlight the darkest cases. Out of the 54 buildings, **14 were found compliant (26 %).**	The corresponding building code is shown in red to highlight the darkest cases. Out of the 54 buildings, **13 were found compliant (24 %).**
Paper II, page 261, Figure 4	The data bar for development "B" **is shown in green**	The data bar for development "B" **should be shown in white**
Paper II, page 264, section 5.1	Out of 54 evaluated buildings, **only 14 were found compliant with the current recommendation (26 %)**, which is a low compliance rate.	Out of 54 evaluated buildings, **only 13 were found compliant with the current recommendation (24 %)**, which is a low compliance rate.
Paper IV, page 6, Table 3	The rotated factor loading (varimax) on Brightness for the scale "Drab - Clear" is equal to **00822**.	The rotated factor loading (varimax) on Brightness for the scale "Drab - Clear" should be equal to **0.822**.
Paper V, page 10, Figure 10 caption	Figure 10: Comparison of responses **for B vs L**, N = 17 (left) and B vs L, N = 6 (right).	Figure 10: Comparison of responses **for B vs K**, N = 17 (left) and B vs L, N = 6 (right).

Paper 1

Building and Environment 191 (2021) 107594

Contents lists available at ScienceDirect

Building and Environment

journal homepage: http://www.elsevier.com/locate/buildenv

Swedish daylight regulation throughout the 20th century and considerations regarding current assessment methods for residential spaces

Iason Bournas

Energy and Building Design, Department of Architecture and Built Environment, Box 118, SE, 22100, Lund, Sweden

ARTICLE INFO

Keywords:
Daylight
Policy
Review
Residential
Building regulations

ABSTRACT

Daylight availability for buildings has been an integral part of architecture since ancient times, yet for the vast majority of countries, criteria for daylight provision were not normative until the 20th century. This article examines the case of Sweden, where the term “daylight” first appeared in regulations in 1960, and assesses the daylight compliance of multi-dwelling buildings before and after that, in the timespan between 1920 and 2000. Firstly, the study evaluates whether the introduction of daylight criteria improved building performance. Secondly, the two current assessment methods are compared, as a disagreement was expected given that one method is formulated based on the glass-to-floor ratio scheme (GFR-method) while the other on a daylight factor scheme (DF_P). Thirdly, the applicability and limitations of each method are evaluated. Results indicate that dwellings built following the introduction of daylight criteria do not necessarily outperform their predecessors. With respect to assessment methods, it was shown that the GFR-method is of limited applicability due to geometric constraints stipulated in its formulation, primarily due to the violation of the fenestration width condition. When comparing methods, the GFR-method yielded higher compliance compared to DF_P, but only marginally. Eventually, the study highlights methodological flaws in the formulation of each criterion. Overall, the work contributes to knowledge supporting the development of daylight requirements for residential spaces. It provides background information suitable for planners and policy makers in their endeavors to define daylight performance criteria.

1. Introduction

Daylight admission for room interiors has always been a goal of architectural practice despite not being stipulated by formal policy explicitly until the 20th century. Formulating universal design criteria for use by practitioners of architecture has proven to be a difficult task, due to the intrinsic nature of daylight, and due to what has previously been a limited capacity to predict illumination accurately via simulation tools. In addition, there has been no consensus as to the way that a daylighting standard should be formulated [1–5]. Relevant literature [6,7] suggests that daylight legislation has been based historically on either one of the following: i) based on access to sunlight (solar zoning), ii) based on window size and iii) based on quantity of illumination. The first type of legislation stipulates that particular parts of buildings should have access to direct sunlight for an adequate length of time. The second type, which is found in building codes most often [8], requires that rooms are equipped with large enough window openings, the window area used as a proxy of actual indoor illumination. The third type, which is currently making its way to international standards, certification systems and national building codes, relates to minimum indoor illuminance levels, i.e. it refers to measurements (or predictions) of luminous flux. During the course of the 20th century, Sweden has formally stipulated daylight criteria of the second and third type.

Swedish building codes did not account for provision of daylight illumination per se until 1975, yet there were eras in the 20th century when residential rooms were provided with large fenestration areas, and spacing between buildings was considered [9,10]. This indicates an intention to provide natural illumination prior to the introduction of explicit daylight criteria. Formal criteria were initially developed as a counter-policy to the energy regulations following the 1973 oil crisis. Since windows constitute the weakest thermal barrier of the building envelope, these energy regulations effectively constrained fenestration sizes as a means to reduce the heating demand. This deemed daylight design rules necessary to prevent large reductions of fenestration, to ensure that natural illumination is preserved. However, despite their introduction, quantified daylight criteria in Sweden were always stated as “general recommendations”. General recommendations are lower in the Swedish regulatory hierarchy, and they are not legally binding [11].

E-mail address: iason.bournas@ebd.lth.se.

https://doi.org/10.1016/j.buildenv.2021.107594
Received 27 September 2020; Received in revised form 13 December 2020; Accepted 4 January 2021

They state what *can be done* to meet "mandatory provisions", which in turn are qualitative. For instance, the current mandatory provision pertaining to daylight states: *rooms or separable parts of rooms where people are present other than occasionally shall be designed and oriented to ensure adequate access to direct daylight is possible, if this does not compromise the room's intended use* [12]. To achieve this, the general recommendation given is either to ensure a minimum room glass-to-floor ratio of 10% (GFR-method criterion) or to meet a daylight factor threshold of 1% on a specific point in the room (DF_P criterion). The GFR-method in particular is only applicable if certain room geometry conditions are met; if not, the DF_P assessment should be used. There are three reasonable assumptions that can be deducted from the aforementioned. Firstly, it is not necessary that all rooms built after 1975 were designed as per the quantified criteria, since the latter were recommendations, not normative. Secondly, the glass-to-floor ratio criterion may not always be applicable, since certain rooms may not meet the geometry conditions it stipulates. Thirdly, the two criteria may not agree for all room cases, since they are formulated differently. This paper aims to evaluate the validity of these three assumptions. In addition, it aims to highlight inherent limitations of each criterion.

1.1. Objective

The paper begins with a review of Swedish building regulations, focusing on daylight criteria. To this end, all norms issued since the term "daylight" was first mentioned in 1960 were examined. Relevant sections and formulations were extracted from each norm to synthesize a timeline of daylight regulation. Subsequently, the daylight compliance of a representative sample of multi-dwelling rooms ($n = 10888$) was assessed according to the DF_P and GFR-method criteria. Linked to the daylight compliance of these rooms, three hypotheses were examined. Firstly, it was hypothesized that the introduction of daylight criteria improved the daylight performance of buildings historically. To this end, the era of regulation (post 1975) was compared to three previous eras of the 20th century in terms of compliance. Secondly, it was hypothesized that the GFR-method is not applicable as an assessment method for all analyzed rooms. To evaluate this, all rooms were characterized geometrically to test whether they violate the geometry conditions stipulated by the GFR-method. Thirdly, for those rooms that the GFR-method was applicable, it was hypothesized that the two criteria would not always yield the same compliance [pass or fail]. This stems from the fact that the GFR-method is based on geometry measures, while DF_P is based on a daylight factor measure. As a final part, the study aims to highlight methodological flaws in the formulation of each criterion, which may reveal the need for new criteria today.

2. Review of Swedish daylight regulation

The daylight regulatory framework for Swedish residential spaces started to develop in 1960s, but became more specific in 1975 as a counter-policy to the energy regulations following the 1973 oil crisis. The following paragraphs describe the evolution of daylight criteria in Swedish building codes over time. Fig. 1 illustrates when different criteria came into force.

2.1. First mention of "daylight", hygiene prioritized

The term "daylight" was first mentioned in regulations in building code BABS 1960 [13], which constituted *an attempt to obtain uniform regulations across Sweden, as opposed to previous local regulations* [14]. Under section 57:2 "General facilities of staff rooms" and in subsection 57:26 "Window", it is mentioned: *Dining rooms should have windows to the outside, which, unless otherwise used by the ventilation system, should be openable. Even in changing rooms and laundry rooms, daylight should be sought.* This mention however cannot be regarded as a strong intent to ensure daylight availability. It was more an intent to ensure hygiene in utility rooms (laundry rooms, drying rooms, toilet rooms, etc.). Reading through the rest of the section reveals that hygiene is the dominating factor of design instructions: *Staff rooms should be so arranged and furnished that personal hygiene is promoted.* Daylight provision for main rooms, i.e. living rooms, bedrooms and kitchens, was considered self-understood for architects of that era. There was therefore no imperative need to define daylight design rules yet, not until the next decade.

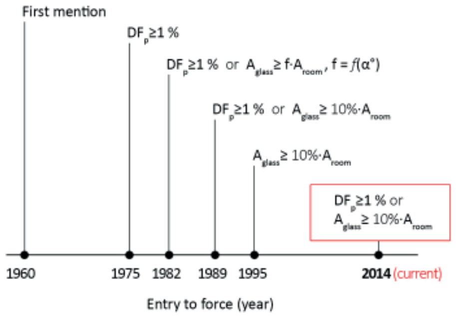


Fig. 1. Evolution of Swedish daylight criteria for residential spaces. DF_P: Point Daylight Factor, A_{glass}: Glazing area, A_{floor}: Room floor area, α°: Glazing obstruction angle.

The following building code SBN-67 [15] that came into force in 1968 included no mention of the term "daylight". The Swedish National Board of Housing, Building and Planning (BOVERKET [16]), which issues building regulations today, describes the main aim of this code as *to design the regulations as functional requirements and to coordinate all regulations relating to house construction* [14]. The absence of a daylight mention can be attributed to the fact that this code included more details with respect to ventilation hygienic flows for utility rooms, which effectively meant that windows for air intake were not an absolute necessity anymore. Relevant literature suggests that indeed this code prioritized building services and technical solutions for hygiene [17]. Unfortunately, the timespan between 1961 and 1975, which included either a qualitative mention for utility rooms (1961–1968) or no mention (1968–1975), was a period of urbanization and rapidly growing demand for housing. It was characterized by historically high rates of new residential constructions ("Record Years"), and the famous Million Homes Programme [18].

2.2. Energy crisis and the formulation of quantified daylight criteria

The first formulation of a quantified daylight criterion was made in 1976, with code SBN-75 [19]. In Chapter 38, section 38:1, it was stated that daylight was considered acceptable *if a daylight factor of 1% is achieved for a point located halfway through the room depth, 1 m from the darkest lateral wall, 0.8 m above floor level* ($DF_P \geq 1\%$). Fig. 2a shows the location of the DF_P point in a room. The criterion was set for *residential rooms, such as living rooms, bedrooms and kitchens, as well as children's playrooms*. Interestingly, another section referring to thermal insulation (section 33:2) stated that *the window area is determined with regard to the requirement for good energy use, however taking into account the requirements for daylight in Chapter 38.* The latter confirms that daylight was initially regulated to avoid dramatic reductions of fenestration to meet energy requirements. These regulations notwithstanding, Marsh refers to the decade following the oil crisis (1975–1985) as the "fabric heat-loss paradigm" in Scandinavian regulations, and argues that this paradigm resulted in low indoor daylight levels [20]. Sweden in

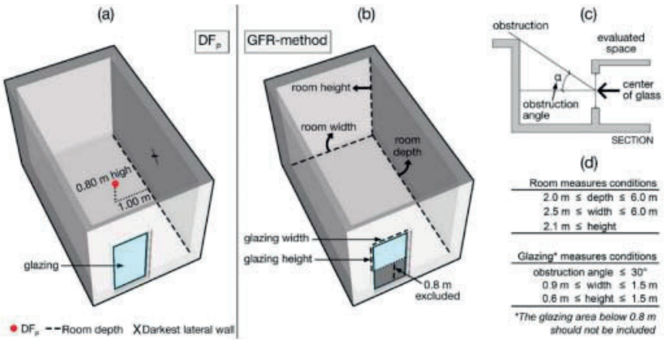


Fig. 2. a) Location of calculation point (red point) for the DF$_P$ assessment, b) room and glazing measures relevant to the GFR-method assessment, c) glazing obstruction angle measure and d) geometry conditions for the GFR-method applicability. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

particular subsidized energy saving measures in the residential sector in a large scale between 1974 and 1983 [21]. Considering the focus on reducing space heating, it can be inferred that inserting a quantified daylight criterion at that time was a wise choice, but it would have been wiser if it were a "mandatory provision" instead of a "general recommendation".

According to code SBN-75, practitioners were instructed to calculate DF$_P$ as per the Daylight Factor calculation method provided by Fritzell and Löfberg [22], which involved the use of a daylight protractor [23]. The Daylight Factor metric used by the authors was earlier defined and documented in the United Kingdom in 1963 by Hopkinson [24]. In fact, Fritzell and Löfberg stated that their work was a translation and adaptation of the book "Daylighting" by Hopkinson et al. [25], published in 1966. Due to the complexity associated with using a protractor for calculations, the following code SBN 1980 [26] introduced an alternative method to predict daylight availability, which was based on the room glass-to-floor ratio (GFR-method). This method was described in Chapter 38:1 K of a complementary report "Kommentarer till Svensk Byggnorm" (English: Comments on Swedish Building Code [27]), which included clarifications to SBN-80. It assumed that this minimum window glazing area has a commensurate effect on illumination as a DF$_P$ $\geq$ 1%. The method stipulated that the minimum glazing area should be equal to the product of the room floor area and a factor f ranging between 0.07 and 0.13 ($A_{glass} \geq f \cdot A_{room}$) depending on the glazing obstruction angle α° (see Fig. 2c for the definition of obstruction angle). This assessment method effectively stipulated minimum glazing areas between 7% and 13% of the room floor area, depending on surroundings. If a balcony obstructed the façade, the considered room floor area would have to include the balcony area adjacent to the façade. The method was applicable only under specific conditions pertaining to room depth, width and height, and glazing width and height (Fig. 2b, c & 2d). It was also not valid for obstruction angles higher than 30°. For rooms violating these conditions, the DF$_P$ method were to be used instead, aiming for a DF$_P$ $\geq$ 1%, calculated using a daylight protractor as per Fritzell and Löfberg [22].

2.3. Simplification of criteria and deregulation

In the years following 1982, energy regulations progressed, demanding ever-lower heating demands for residences, while daylight criteria lagged behind. In 1989, code BFS 1988:18 [28] simplified the GFR-method calculation by replacing factor f with a constant, i.e. it removed the sensitivity to surrounding obstructions. The new code simply stipulated that the glazing area would have to be no less than 10% of the room floor area ($A_{glass} \geq 10\% \cdot A_{room}$), a glass-to-floor ratio that is commonly used in national codes [8]. The code included a note that *in cases of obstruction angles higher than 20°, the glazing area should be increased*, but it did not specify the magnitude of this increase. This simplified GFR-method was regulated at a time when Stockholm made a crucial transition in urban planning: the shift from expansion to densification [29]. In essence, planning tendencies focused more on central areas, using high building volumes to satisfy housing demands. Urban density and self-shading of buildings resulted in a higher amount of dim rooms, as it is shown in section 4.2.1. As before, if a room violated any geometry condition (Fig. 2d), practitioners would have to calculate DF$_P$ according to standard SS914201 [30]. The DF$_P$ calculation method was the one introduced in 1975 (using daylight protractors), and it seems it did not find acceptance among practitioners. From 1995 [31] until 2014 [32], the quantified DF$_P$ $\geq$ 1% criterion was completely removed from building codes, which only included the simple GFR-method ($A_{glass} \geq 10\% \cdot A_{room}$). A reasonable explanation is that the DF$_P$ calculation was too complicated to be adopted on a large scale, compared to a simple geometry calculation. Effectively, the $A_{glass} \geq 10\% \cdot A_{room}$ was the only devised daylight criterion until 2014, not applicable unless geometric conditions were met, and not legally binding.

2.4. Revival of DF$_P$ criterion and current state

When code BFS 2014:3 [32] came into force, the DF$_P$ $\geq$ 1% criterion was re-instated, as advances in computation made it easier for practitioners to calculate accurate DF$_P$ values by means of simulation software instead of daylight protractors. Simulation tools validated for agreement with full-scale spaces were now readily available and compatible with CAD software already adopted by the industry. Soon after its revival, an increased interest was expressed towards modernizing the DF$_P$ criterion [17]. On the other hand, building developers voiced their concerns regarding potential design constraints stemming from daylight requirements, threatening the profitability of their investments. Researchers suggest that a suitable criterion for large-scale application needs to satisfy both technical and economic aspects [4,33]. The current state in Sweden points towards some degree of compromise between the two. It seems that the technical aspects will be satisfied by adopting a method closer to European Standard EN17037 [34], which is considered by the Swedish National Board of Housing, Building and Planning as being superior to the DF$_P$ calculation method. As for the financial aspect, it seems it will be satisfied by excluding spaces from evaluations, for instance the kitchen space, as recently proposed by the Building Rules Modernization Committee [35]. The motivation for this exemption was that in many apartments it is not possible to have a window for all rooms, and that social spaces (e.g. living room, dining room) and bedrooms should be prioritized in terms of fenestration and views-out, and consequently in terms of daylight [36]. The proposal report of the Building Rules Modernization Committee also referred to a study of the construction industry's research and development organization SBUF [37], which stated that deviations from current criteria, including daylight criteria, could lead to accommodating 40% more apartments in a residential area [38]. According to the government, this committee was appointed in 2017 to *modernize the regulations and thereby promote increased competition and increased housing construction without compromising health, safety, quality of design, a good living environment and long-term sustainable construction* [39].

3. Methodology

This section describes the methods used to evaluate the effect of regulation on building daylight performance historically, and to assess the usability and reliability of the criteria currently in force. The following subsections provide details on i) the type of multi-dwelling buildings assessed for daylight compliance, ii) the distinct eras of the 20th century that were compared, and iii) the methods used to analyse data.

3.1. Selected developments

3.1.1. Location and urban density

The study included a sample of diverse multi-dwelling building blocks, located in urban areas of the central and metropolitan region of Stockholm. According to definition, multi-dwelling buildings comprise at least three apartments. In Sweden, they are the most common type of residence [40], and the most common building type used in new construction annually since 1985 [41]. The developments were selected according to construction year and building typology in order to acquire a representative sample, as described in the following section. Overall, 25 residential developments were included, comprising 54 buildings with 3151 apartments, making for 10888 individual rooms. Fig. 3a shows the locations of developments (n = 25, codes A - Y). Following the current building code, only rooms "where people are present other than occasionally" were considered. The rooms included: i) kitchens (K: n = 3025), ii) living rooms (L: n = 2879), iii) bedrooms (B: n = 3792) and iv) dining rooms (D: n = 1192).

To evaluate the effect of surrounding obstructions on daylight performance, the urban density [m^3/m^2] indicator was calculated per development. For a given building, urban density is calculated as the volume of surrounding buildings divided by the land area they occupy, in a specific radius from the evaluated building. This indicator is used to quantify urban density and has been shown to associate strongly with irradiation on building facades [42]. The considered area is shown in Fig. 3b for development X, where the blue polyline is the planar convex hull of the endpoints of the footprint outline (black points), shown indicatively on the top left of figure. A convex hull for a set of points *S* in the Euclidean space is the smallest convex set containing *S* [43], i.e. the smallest-area polyline that is convex and contains the development. Surroundings were considered within a 250 m offset of the convex hull (dark grey footprints in Fig. 3b).

3.1.2. Typology of selected building blocks

The evaluated developments were selected to represent eight block typologies commonly adopted in Swedish urban planning history, as categorized by Hall and Rörby [29], and by Rådberg and Friberg [44]. Fig. 4 illustrates all included developments (A – Y), with information on typology (1–8), number of rooms and construction year. The construction year was also considered in the sample selection process. In particular, the number of selected apartments per decade was proportional to the number of apartments constructed during each decade. Characteristics of typologies are described briefly below. Numbering (1–8) corresponds to the numbering in Fig. 4, and development codes are given for each typology:

1. *Low-rise towers* ("låga punkthusgrupper") – A, O, U: These buildings have a concentrated plan, typically comprising four apartment units around a central stairwell. They usually reach up to four stories in height, with corner rooms usually being double-aspect.
2. *High-rise towers* ("höga punkthusgrupper") – G, H, M: Their plan is similar to that of *Low-rise towers*, and the height can reach up to 16 stories. They were developed mainly in suburbs, as a means to house multiple tenants all while retaining adequate daylight and ventilation. They represented the modernist ideal image of the "house in the park" [44].
3. *High + Low combination* – C, T, V: Paired buildings, used to extract the advantages of both a tower and a narrow type. The low part could provide sufficient ventilation and daylight for most rooms due to its limited width, which was costly in terms of apartments per stairwell. The high part contributed most apartments, and provided a dramatic elevation profile.
4. *High-rise elongated* (Swedish: skivhusgrupper) – F, J, N, S: Buildings that are at least 50 m long, typically comprising three to four

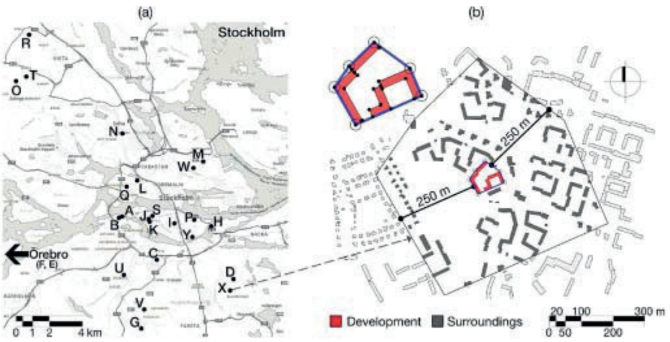


Fig. 3. a) Location of developments on the map and b) extent of accounted surroundings shown for development X (Map data: Google, with additional information).

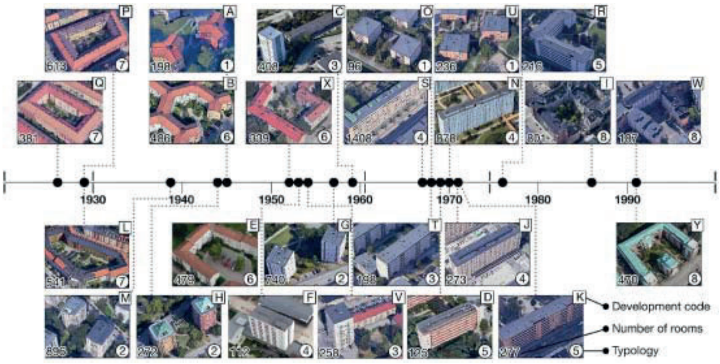


Fig. 4. Timeline including aerial views of selected developments (A–Y), with corresponding construction years, numbers of rooms and typology categories. The dashed lines intersecting the timeline divide it into four eras that are compared in terms of daylight performance and are described in detail in section 3.2. (Images: Google, with additional information).

stairwells. They were adopted mainly after 1960, when prefabrication became common, to accommodate a high number of apartments. To this end, they can be considered successors of the *High-rise towers.*

5. *Exterior circulation* (Swedish: loftgånghus) – D, K, R: They were typically used under the Million Homes Programme [18] between 1965 and 1974. They are equipped with a long shared external corridor that provides entrance to individual apartments, thus reducing the number of elevator costs per apartment.
6. *Semi-open courtyard* – B, E, X: They were built primarily in the suburbs, between 1940 and 1960, were typically no higher than three stories, and could be as narrow as 8 m. Their module is the linear narrow building of the 1930s, but now arrayed in formations that create semi-open, private courtyards.
7. *Large courtyard* – L, P, Q: They emerged after the 1907 Town Planning Act [45], which effectively banned the previous practice of constructing building rows within courtyards, thus made way for large empty courtyards. They were commonly adopted in metropolitan inner parts as a "reform", manifested with a visually uniform building, which surrounded a large, park-like, inner courtyard [29].
8. *Post-modern reforms* – I, W, Y: They are the result of the intent after 1975 to adopt older block types (prior to 1930, *Large courtyard* blocks), but with a more blurred limit between the street and the private courtyard, and with increased building height.

3.2. Distinct periods (eras) of the 20th century

The evaluated buildings were grouped intuitively into four periods (eras) according to urban planning history and daylight regulation during the 20th century. Fig. 5 shows a timeline including these eras, and the daylight regulation in effect during each one. These eras were compared to evaluate whether the introduction of daylight regulations affected the performance of buildings historically:

1. The first era (until 1930) was characterized by inner city building blocks following the 1907 Town Planning Act; it is represented by *Large courtyard* buildings in this study.
2. The second era (1930–1961) was characterized by functionalist architecture, urban expansion and the development of suburbs. It is represented by *typologies Low-rise towers*, *High-rise towers*, *Semi-open courtyards* and *High + Low combinations.*
3. The third era (1961–1975) is known as the "Record Years". It is characterized by a historically high rate of new building constructions, which included the large-scale developments of the Million Homes Program. Typologies during this era included *Low-rise Towers*, *High + Low combinations*, *High-rise Elongated* and *Exterior circulation.*

No daylight evaluation criteria were effective during the three aforementioned eras.

4. The fourth era (1975–2000) corresponds to the final quarter of the century, which followed the 1973 oil crisis and saw a high degree of energy policy for buildings, as well as a shift towards urban densification. It is represented in this study primarily by *Post-modern reforms*, and by one *Exterior circulation* typology. This is the only period during which daylight criteria were present in the building code.

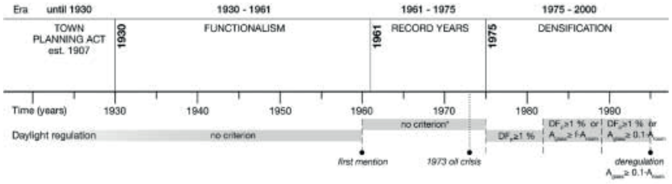


Fig. 5. The four distinct eras and daylight regulation timeline. *There was actually no quantified criterion in force during era "1961–1975", only a general mention on daylight provision in staff rooms.

3.3. *Applicability of the GFR-method*

As stated previously, practitioners are given two alternatives for assessing daylight compliance (DF$_P$ and GFR-method). However, if the GFR-method is not applicable due to violations of the conditions in Fig. 2d, the DF$_P$ assessment should be used. The study assessed the probability that the GFR-method is applicable (applicability) in different groups of rooms. The applicability was calculated as the percentage of GFR-method compatible rooms in a given group (e.g. percentage of compatible kitchens). To evaluate which geometry condition is violated more often, the geometric measures stated in Fig. 2d were considered separately, counting the compatible rooms per condition.

3.4. *Compliance rates*

Each room was tested for compliance with both criteria, namely: i) DF$_P$ $\geq$ 1% and ii) GFR $\geq$10%. Data were further processed to acquire compliance rates of specific groups, i.e. percentage of compliant rooms within these groups. These groups included i) function groups (K, L, B, D), ii) era groups ("until 1930", "1930–1961", "1961–1975", "1975–2000") and iii) regulation groups (unregulated rooms (pre 1975), regulated rooms (post 1975)).

3.5. *Data analysis*

Table 1 includes a summary of the statistical tests used, the corresponding groups and calculated statistics per test. The following subsections describe the assumptions for each test.

3.5.1. *Chi-square test of independence*

To test whether room DF$_P$ compliance [0 = fail, 1 = pass] is associated with room function or era, Chi-square tests of independence were used. The Chi-square test of independence analyzes group differences (e.g. kitchens vs living rooms) when the dependent variable is measured at the nominal level (e.g. compliance = 0 or 1), and the groups are independent. It is robust with respect to data distribution, and does not require equal variances or homoscedasticity. It is applied on a contingency table, in this study a 2 × 2 table. The test only assesses the significance of the difference between the groups, i.e. assesses whether a difference exists, not how large it is. The magnitude of the difference must be assessed by a strength statistic [46]. The appropriate strength statistic is Cramer's V [47], which ranges from 0 if the groups are independent of the variable (e.g. if room function is not predictive of compliance), to 1, if the groups are perfectly predictive of the variable (e.g. if room function is predictive of compliance). According to Cohen [48], a Cramer's V that is equal to 0.1, 0.3 or 0.5 corresponds to a weak, medium or large effect respectively (for a 2 × 2 contingency table). In this study, differences with Cramer's V values higher than 0.3 were considered of meaningful magnitude.

3.5.2. *McNemar's test*

To test whether the choice of assessment method (DF$_P$ or GFR-method) affects compliance [0 or 1] of rooms, the McNemar's test was deployed. The McNemar test can be used to compare binary nominal variables (e.g. compliance = 0 or 1) between paired groups (e.g. DF$_P$ compliance vs GFR-method compliance), and is suitable for non-parametric data [49]. The test statistic is calculated based only on the number of pairs with different compliance (discordant pairs), for instance, a discordant pair of compliances for a room could be "DF$_P$ compliance = 0, GFR-method compliance = 1". Rooms with the same compliance (1 = 1 or 0 = 0, concordant pairs) are not considered for the calculation of the test significance (p-value). Since McNemar's test only assesses significance, the Odds Ratio (OR) must be calculated to assess effect size [50], in this case, how large is the effect of method choice on compliance. An OR that is significantly higher than 1 provides evidence that there is a substantial effect, measured by the size of the OR. To assess that OR is significantly higher than 1, the 95% Confidence Interval (CI) of the OR value must be constructed [50], and it should not include 1. Therefore, an effect was considered meaningful for an Odds Ratio greater than 1 and a 95% CI that did not include 1.

3.5.3. *Mann-Whitney U test*

The distribution of DF$_P$ [%] was compared between regulated rooms (post 1975) and unregulated rooms (pre 1975) using a Mann-Whitney *U* test, to evaluate whether the introduction of daylight criteria improved daylight performance historically. By definition, the Mann-Whitney U statistic estimates the probability that a random score from one sample (e.g. a random DF$_P$ value among regulated rooms) exceeds a random score in a second sample (e.g. exceeds a random DF$_P$ value among unregulated rooms) [51]. The test was appropriate here as i) DF$_P$ was not normally distributed across rooms of each group, ii) the compared groups were independent (i.e. no room was included in both groups), and iii) there were DF$_P$ outliers in the distributions of both groups. Results were considered significant when $p < 0.05$. The test assesses significance, and has to be complemented by an effect size calculation to assess the magnitude of the effect (e.g. the effect of regulation on DF$_P$ distribution). For the Mann-Whitney *U* test, the appropriate effect size is Cohen's r [52]. Cohen suggests that an effect size r equal to 0.1, 0.3 or 0.5 indicates a small, medium or large effect respectively [48]. One group was considered to have substantially higher DF$_P$ values compared to the other when r was higher than 0.3.

3.5.4. *Spearman Rank correlation*

The Spearman Rank correlation coefficient r$_S$ was used to measure the strength of association between DF$_P$ and GFR across a sample of rooms where the GFR-method was applicable, to evaluate the agreement between the two assessment methods. The variables where not normally distributed, which is why r$_S$ was preferred, as it is more robust in cases of heavy-tailed distributions or when outliers are present [53]. The statistic can be interpreted according to the three-tier categorization suggested by Cohen [48], where the effect is considered small, medium or large for

Table 1
Summary of statistical tests used to compare daylight compliance between different groups of rooms, including the effect size per test, the size (n) of each group and the variable evaluated.

Test	Effect size	Groups	n	Variable
Chi-Square test of independence	Cramer's V	until 1930	3025	DF$_P$ compliance [0 or 1]
		1930–1961	2879	
		1961–1975	3792	
		1975–2000	1192	
		K, L, B, D per era	see Table 2	DF$_P$ compliance [0 or 1]
McNemar's test	Odds Ratio	rooms where GFR-method is applicable	2675	DF$_P$ and GFR compliance [0 or 1]
Mann-Whitney *U* test	Cohen's r	regulated rooms	1674	DF$_P$ [%]
		unregulated rooms	9214	

an absolute value of r_S lower than 0.3, between 0.3 and 0.5, and greater than 0.5 respectively. Associations with $r > 0.3$ were considered as meaningful in this study.

4. Results and discussion

This part includes two distinct sections, i) initial findings pertaining to geometry (section 4.1) and ii) main results (section 4.2). Section 4.1 pertains to derived geometry measures and characteristics per room function and era. It also includes the evaluation of the GFR-method applicability. The generation of these data preceded simulations, and the data serve as complementary information supporting the main findings presented later on, in section 4.2.

4.1. *Initial findings pertaining to geometry*

4.1.1. *Room measures*

Fig. 6 shows the distribution of each geometry measure pertaining to the GFR-method, per room function K, L, B, D. It is shown that room height (c), glazing obstruction angle OA (d) and glazing height (f) do not vary significantly between functions. Living rooms (L) are substantially deeper (a), wider (c), and equipped with wider fenestration (e), compared to the rest of the rooms, while kitchens (K) are relatively narrower (b) and with less wide glazing (e). Dining rooms seem to be favored for daylight admission more often, as they are the least deep rooms (a), with less surrounding obstructions (d) compared to the rest of the functions. Considering that the GFR-method is only applicable under certain geometry conditions, it is evident that not all rooms may be assessed using it, for instance there are cases with obstruction angles greater than 30°. The applicability of the GFR-method is assessed in the following section 4.1.2.

Table 2 shows characteristics of rooms per era and function, including quartiles Q1, Q2 and Q3 for GFR and OA. In cases of multiple windows, GFR and OA are calculated as weighted averages based on glazing area. Additionally, Table 2 includes percentages of rooms that are windowless or have a balcony obstruction, and the urban density range per era (right-most column). With respect to eras, it is shown that rooms with larger GFR and fewer obstructions (OA) were primarily designed in era “1930–1961”. For this era, GFR is shown to be greater than 12% for at least 75% of each room function (Q1), while at least 50% of rooms (Q2) have OA lower than 5%. Another characteristic of this era is that its dwellings were built in the least dense zones (0.74–3.68 m^3/m^2). Rooms of the following era (”1961–1975”) have relatively low obstructions (OA lower than “until 1930” or “1975–2000” eras) and high GFR, but have two characteristics that can deprive them of daylight admission. Firstly, they include a high amount of windowless rooms (9.1% of rooms in this era). Secondly, 32% of the rooms in this era are obstructed by a balcony, which includes all room functions, mainly due to the adoption of *Exterior circulation* typologies (section 3.1.2). Eras “until 1930” and “1975–2000” include buildings in the most densified urban zones, and have consequently rooms that are obstructed to a higher degree (Q2 for OA in these two eras is substantially higher). Also contributing to obstructed windows for the rooms of these eras is the courtyard block type (Fig. 4, typology 7), which results in self-shading.

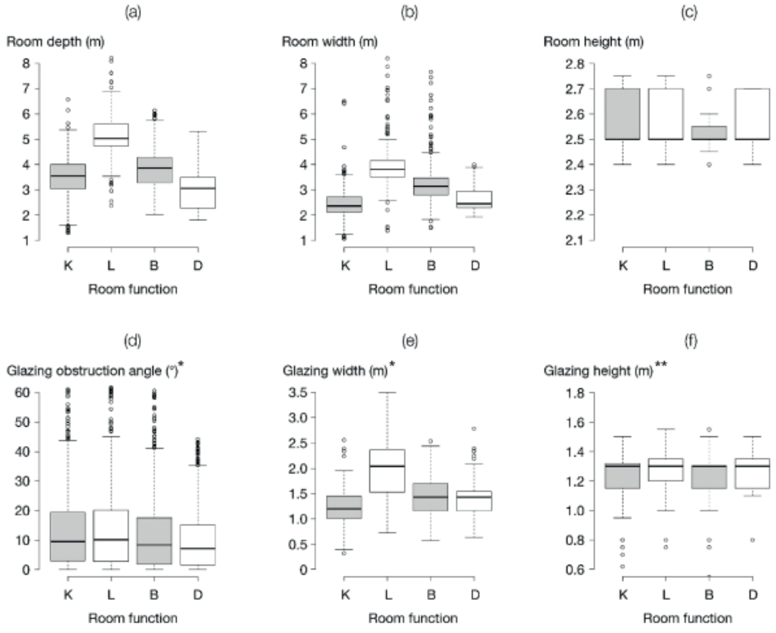


Fig. 6. Distribution of geometric measures per room function: Room a) depth, b) width, c) height, glazing d) obstruction angle, e) width and f) height. Figures (a), (b) and (c) include all evaluated rooms ($n = 10888$). Figures (d), (e) and (f) include only fenestrated rooms ($n = 10212$). *In cases of rooms with multiple windows, the largest obstruction angle and width are reported here. **Any glazing area below 0.8 m above floor level is not considered for the calculation of glazing height (Fig. 2b).

Table 2
Room data per function (K, L, B, D) and period (era), including number of rooms, quartiles Q1, Q2 and Q3 for glass-to-floor ratio (GFR) and obstruction angle (OA), percentage of rooms without fenestration (Windowless), with a balcony obstruction (Balcony), and range of urban density. Quartiles Q1, Q2 and Q3 for GFR and OA are calculated including only fenestrated rooms.

Era (time period)	Room		GFR (%)[a]			OA (°)[a]			Windowless (%)	Balcony (%)	Urban density (range, m^3/m^2)
	Function	Number	Q1	Q2	Q3	Q1	Q2	Q3			
until 1930	K	647	10.6	13.8	15.8	8.9	14.7	24.7	24	1	3.79–5.46
	L	492	9.3	13.6	15.2	8.8	14.0	24.1	0	7	
	B	245	12.2	13.5	15.6	10.3	16.1	26.1	0	0	
	D	151	17.3	17.9	18.9	10.4	15.5	23.2	0	0	
1930–1961	K	1138	15.1	15.5	17.0	0.0	4.5	11.4	16	1	0.74–3.68
	L	1159	13.2	17.2	23.4	0.0	4.6	10.8	0	82	
	B	1329	12.1	14.2	15.3	0.0	3.9	11.6	0	20	
	D	562	23.6	23.9	26.8	0.0	2.9	10.8	0	17	
1961–1975	K	806	10.7	13.5	18.5	4.0	8.7	17.3	38	29	1.55–4.09
	L	794	12.7	15.3	18.8	2.1	9.7	18.2	0	20	
	B	1429	10.9	16.9	22.2	3.3	9.1	18.3	0	44	
	D	462	13.5	21.9	33.4	4.3	8.3	14.3	3	22	
1975–2000	K	434	12.0	13.3	13.9	6.8	15.4	25.9	1	65	1.68–5.30
	L	434	9.1	10.5	13.3	5.6	13.4	22.5	0	72	
	B	789	10.6	11.9	14.2	4.9	9.9	17.6	0	12	
	D	17	11.4	36.5	53.5	0.1	16.7	26.3	71	0	

[a] *Glazing area-weighted average GFR or OA in cases of rooms with multiple windows.*

With respect to room functions, it is evident that kitchens (K) are more often placed deeper in the building core as windowless rooms that are illuminated indirectly by another room (normally by a dining room). This is true for all eras. Dining rooms have by far the highest GFR (Q2 for GFR, all eras), which was already implied by the data in Fig. 6. It should be noted here that in buildings of the latter era (*1975 – 2000*), dining was taking place in an area integrated within kitchen rooms, instead of occupying a distinct room or area away from the kitchen cabinets. The room function in these case was considered as "kitchen", which explains the low number of D (n = 17).

4.1.2. Applicability of GFR-method

Fig. 7 shows the applicability (white) and inapplicability (grey) of the GFR-method according to each geometry condition, for instance, the GFR-method is not applicable in 5% of the rooms due to their depth. All rooms (n = 10888) were included for the room conditions (bars on the left), while only fenestrated rooms (n = 10212) were considered for the glazing conditions (bars on the right). It is more common for the GFR-method to be inapplicable due to violations pertaining to glazing geometry. The most commonly violated condition is glazing width (51% of rooms violate this condition), which should lie between 0.9 and 1.5 m. The second most common cause is room width, which should lie between 2.5 and 6.0 m. The rest of the conditions are met by the vast majority of rooms.

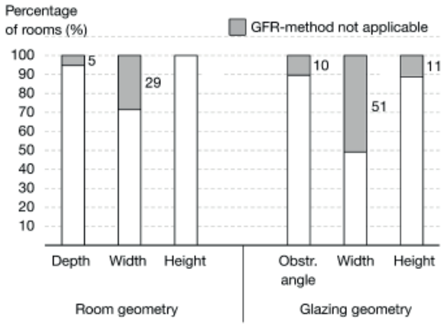


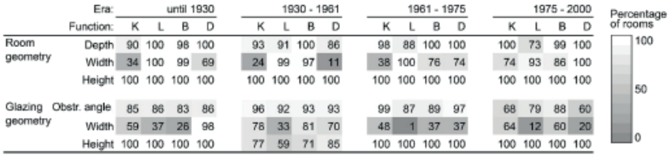
Fig. 7. GFR-method applicability according to room geometry conditions (n = 10888, bars on the left) and glazing geometry conditions (n = 10212, bars on the right).

Fig. 8 shows the GFR-method applicability per condition, for each era and function. The values are shaded according to the degree of applicability, from white (100% applicability) to dark grey (zero applicability). With respect to eras, it is shown that the conditions for room and glazing width are normally violated by at least one function. Overall, the applicability for eras "until 1930", "1930–1961" etc. is 27.8%, 25%, 19% and 32.3% respectively, which is very low. Notable differentiations of eras include the violation of the glazing height condition in era "1930–1961", and the violation of the obstruction angle condition in era "1975–2000", which is in line with the densification trend during that era. With respect to room functions, it is shown that kitchens violate the room width condition more often compared to other functions. These kitchens include narrow elongated rooms (as narrow as 1.1 m corridor kitchenettes). Dining rooms were also narrower than the minimum allowed 2.5 m width (see Fig. 6b), often positioned in the same plan grid as the kitchen, hence the relation between kitchen and dining room applicability in Fig. 8. Another notable finding relates to living rooms of the latter two eras, which violate the glazing width condition at a high rate even though they comply with the room width condition. There were two different causes for this: there were a few living rooms (8%, considering both eras) with narrow glazed doors (width < 0.9 m) for accessing balconies, and many living rooms (75%) with extensive glazing, as previously indicated by Fig. 6.

4.2. Main results

4.2.1. Compliance per era

Fig. 9 illustrates the DF$_P$ compliance rate per building, with building footprints sorted according to construction year. Footprints with darker tones correspond to buildings with lower compliance rates. The coloration indicates that era "1930–1961" outperforms all other eras. This is in agreement with the preliminary findings, where era "1930–1961" was shown to include rooms with markedly low obstruction angles and high GFR (Table 2). What is interesting is that this era precedes the introduction of normative daylight criteria, which first came into force in 1975. The pairwise Chi-square (Table 3) revealed that DF$_P$ compliance during "1930–1961" was significantly higher compared to other eras ($p < 0.001$), with the effect size ranging from medium when compared



	Era:	until 1930				1930 - 1961				1961 - 1975				1975 - 2000			
	Function:	K	L	B	D	K	L	B	D	K	L	B	D	K	L	B	D
Room geometry	Depth	90	100	98	100	93	91	100	86	98	88	100	100	100	73	99	100
	Width	34	100	99	69	24	99	97	11	38	100	76	74	74	93	86	100
	Height	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Glazing geometry	Obstr. angle	85	86	83	86	96	92	93	93	99	87	89	97	68	79	88	60
	Width	59	37	26	98	78	33	81	70	48	1	37	37	64	12	60	20
	Height	100	100	100	100	77	59	71	85	100	100	100	100	100	100	100	100

Fig. 8. GFR-method applicability according to each geometry condition, per room function per era. Room geometry conditions are tested in all rooms (n = 10888), while glazing geometry conditions are tested in fenestrated rooms (n = 10212).

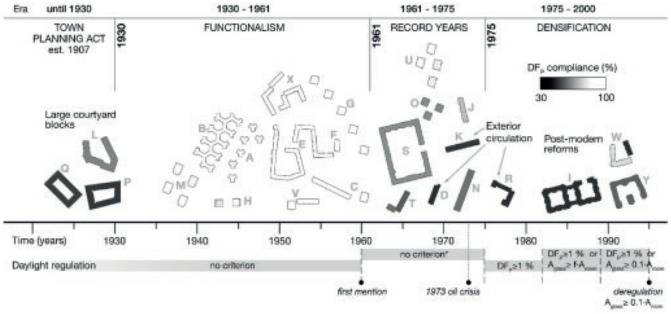


Fig. 9. Building footprints sorted according to construction year and shaded according to DF$_P$ compliance rate. Daylight criteria during each period are shown below the timeline. *During era "1961–1975", there was only a mention on daylight for utility rooms, but no quantified criterion.

Table 3
Cramer's V for pairwise comparison of DF$_P$ compliance [0–1] between eras. Effect sizes that are medium or higher are shown in bold.

era	until 1930	1930–1961	1961–1975	1975–2000
until 1930	–	**0.421**	0.079	0.068
1930–1961		–	**0.349**	**0.485**
1961–1975			–	0.144
1975–2000				–

with era "1961–1975" (Cramer's V = 0.349), to large when compared with era "1975–2000" (Cramer's V = 0.485 ≈ 0.5). The overall DF$_P$ compliance rate per era starting from era "until 1930" was 52.2%, 90.3%, 60.7% and 45.4%. This implies that rooms of the latter era, which is the only one with set criteria, underperform considerably. Reflecting on the exemplary performance of developments of the "1930–1961" era, one may consider the cost to pay when building lower-density developments. Previous research has shown that low-density housing increases infrastructure costs and cannot respond to the needs for rapid urban development [54], which is what main Swedish cities are currently experiencing [55]. Land property constitutes a small proportion of the costs of housing construction in Sweden [56], but the profitability of an investment relies on the amount of apartments per development. Therefore, a financial compensation when spacing buildings could be to densify using high-rise buildings, just as the "High-rise towers", either exclusively or combined with lower buildings ("High + Low combinations").

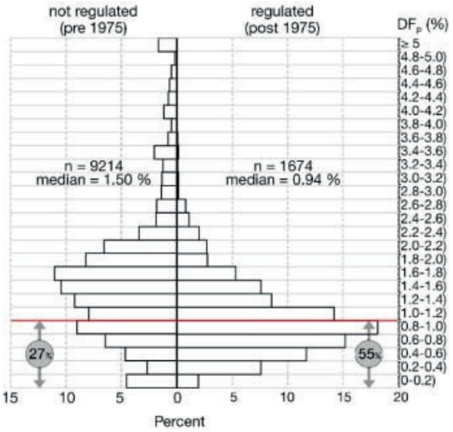


Fig. 10. DF$_P$ percentage histograms for unregulated (n = 9214) and regulated (n = 1674) rooms. The cumulative percentage of incompliant rooms is shown per group. Also shown are the Mann-Whitney *U* test results and Cohen's r.

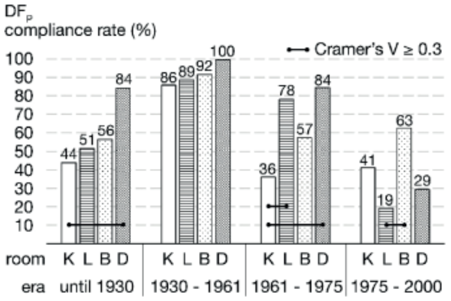


Fig. 11. Room compliance rate according to the DF_P criterion, per function (K, L, B, D) and era. The linear markers connecting functions within eras correspond to large compliance differences as per Cramer's V (≥0.3), i.e. two room functions are connected with a linear marker when the DF_P compliance rate of one room function is significantly higher than that of the other room function.

4.2.2. *Compliance of regulated vs unregulated rooms*

The DF_P difference between regulated (post 1975) and unregulated (pre 1975) rooms is shown in Fig. 10. According to the Mann-Whitney *U* test results, the distribution of DF_P lies significantly higher for buildings built prior to the introduction of daylight criteria compared to buildings of the regulated era (median: $1.50 > 0.94$), with a small-to-medium effect size ($U = 4687273$, Cohen's $r = 0.245$, $p < 0.001$). This is counter-intuitive as there were different criteria in force during era "1975–2000" (see Fig. 5). The majority of regulated rooms fail the meet the DF_P requirement (54.6% fail), and the DF_P distribution does not extend significantly further from $DF_P = 2.8\%$. The corresponding rate for regulated rooms is 27% and the DF_P distribution is skewed, reaching DF_P values greater than 5%. Contributing significantly to the 27% failure rate is era "until 1930", which is represented here by *Large courtyard* blocks. Overall, the results imply that general recommendations are not sufficient for daylight provision, and that the roles of urban planning trends (e.g. densification) and architecture (e.g. building block design) are equally important.

4.2.3. *Compliance per room function*

Fig. 11 shows DF_P compliance rates per room function and era. The linear markers with circular endpoints indicate which pairs of functions have substantially different compliance rates as per the Chi-square tests. With respect to eras, "1930–1961" outperforms all other eras for all room functions. With respect to functions, it is shown that the majority of kitchens are incompliant for all eras except "1930–1961". The opposite is true for dining rooms, which have the highest compliance rates in all eras except "1975–2000". The peculiarity of this era relates to the dining area being integrated to the kitchen room as explained previously under section 4.1.1. Overall, kitchens are the least compliant rooms and dining rooms the most compliant ones. Notable differences within eras (linear markers) include K vs D in era "until 1930" (Cramer's $V = 0.315$, $p < 0.001$), K vs L and K vs D in era "1961–1975" (Cramer's $V = 0.421$ and 0.465 respectively, $p < 0.001$), and L vs B in era "1975–2000" (Cramer's $V = 0.416$, $p < 0.001$). Room functions were also compared considering the overall sample (rooms included in all eras). The most substantial difference was found between dining rooms and kitchens (Cramer's $V = 0.321$, $p < 0.001$), dining rooms and living rooms (Cramer's $V = 0.231$, $p < 0.001$) and between dining rooms and bedrooms (Cramer's $V = 0.202$, $p < 0.001$). This implies the prioritization of dining rooms in terms of daylighting, which were previously shown to outmatch the rest of the functions in terms of GFR (Table 2).

Table 4
Number of rooms that fail both criteria (*a*), pass both criteria (*d*), pass only DF_P (*c*), pass only GFR (*b*), and totals.

	GFR-method fail	GFR-method pass	total
DF_P fail	a 451	b 261	712
DF_P pass	c 94	d 1869	1963
total	545	2130	2675

4.2.4. *Criteria agreement*

This section compares the two compliance criteria ($DF_P \geq 1\%$) and $GFR \geq 10\%$) including only rooms where the GFR-method is applicable ($n = 2675$). The McNemar's test was applied in the 2×2 contingency table shown in Table 4. The table shows the amount of rooms that fail both criteria (*a*), pass both criteria (*d*), pass only DF_P (*c*), pass only GFR (*b*), and totals. The agreement between the two criteria is 87% (451 + 1869), which can be considered high, and the disagreement is 13% (94 + 261). In cases of disagreement, it is significantly more common for the GFR-method to yield compliance compared to DF_P ($OR = b/c = 2.78$, $p < 0.001$, CI: [2.185–3.553]). This indicates that the probability of a room complying with $GFR \geq 10\%$ while not complying with $DF_P \geq 1\%$ is nearly three times higher than the probability of the opposite occurring. Overall 80% ($n = 2130$) of the rooms comply with $GFR \geq 10\%$, while 73% ($n = 1963$) comply with $DF_P \geq 1\%$.

The DF_P and GFR values were plotted to evaluate whether *d* pairs (rooms that comply with both criteria, $n = 1868$) are distributed across extremely high values, i.e. whether the agreement between the criteria is due to saturation of either one of the two criteria. Fig. 12a and b shows scatterplots of the concordant (*a*, *d*) and discordant (*b*, *c*) pairs respectively, along with the number of pairs in each group. It is shown that the *d* pairs cluster close to the criteria threshold values, which indicates that the agreement between criteria is not due to saturation. The association between the two criteria is also indicated by the strong Spearman Rank correlation coefficient for the *d* pairs ($r_S = 0.655$, $p < 0.001$).

4.2.5. *Criteria limitations*

Following are limitations of each criterion, due to their formulation. Fig. 13 shows how the obstruction angle measure can under or overestimate the degree of surrounding obstructions, effectively deeming the GFR-method applicable or inapplicable respectively. The reader is referred to Fig. 2 for the definition of the obstruction angle. Fig. 13a shows a building of the *Post-modern reforms* typology (development Y), which has some visual connection between the street and the public courtyard. The obstruction angle for a room located low in the courtyard is equal to 3.3°, as there is no building volume directly in front of this room. This allows the room to be assessed based on its GFR, which is 15.4% (>10%), thus the room is compliant. However, the same room is not compliant according to DF_P by a high margin ($DF_P = 0.65\% < 1\%$). This room corresponds to one of the 261 *b* pairs in Fig. 12b. On the other hand, Fig. 13b shows a case where a sole tower building in the field of view of a room results in an obstruction angle of 37.8°, although the room has actually a significantly high view of the sky dome. This deems the GFR method inapplicable due to high obstructions, but the DF_P criterion is met ($DF_P = 1.72\%$). It can therefore be concluded that the obstruction angle is not a reliable indicator of obstructions, particularly when the field of view does not include uniform obstructions.

Fig. 14 shows an example where the DF_P value changes critically, from exceeding the compliance threshold (Fig. 14a, $DF_P = 1.08\%$) to failing the criterion (Fig. 14b, $DF_P = 0.84\%$), all while the GFR remains constant above its compliance threshold ($GFR = 10.05\%$). The ratio between room depth and width is shown to affect DF_P compliance, leading to criteria disagreement. This is true particularly for elongated rooms where the DF_P point is located significantly deeper (e.g. 1.20 m difference between the two rooms in Fig. 14). Finally, Fig. 15 illustrates an issue related to the ambiguous definition of the DF_P point location. The room in Fig. 15a has one window and is compliant according to both

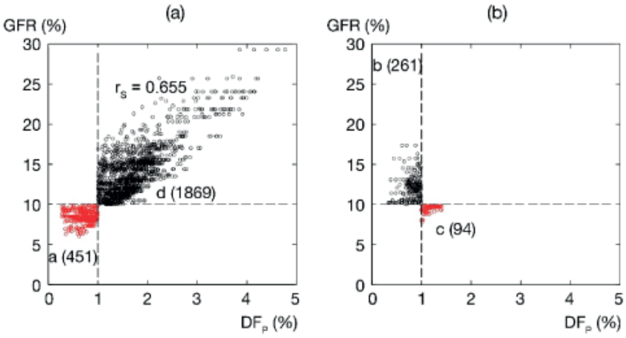


Fig. 12. Scatterplot of a) concordant pairs of GFR and DF_P compliance (*a*: fail both criteria, *d*: pass both criteria) and b) discordant pairs (*b*: only pass GFR, *c*: only pass DF_P). The numbers of pairs in each group are shown in parentheses, and the Spearman Rank coefficient r_S corresponds to the *d* pairs.

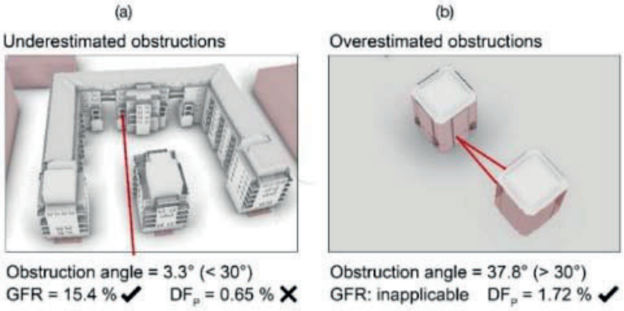


Fig. 13. a) Underestimated obstructions by the Obstruction Angle measure and b) overestimated obstructions.

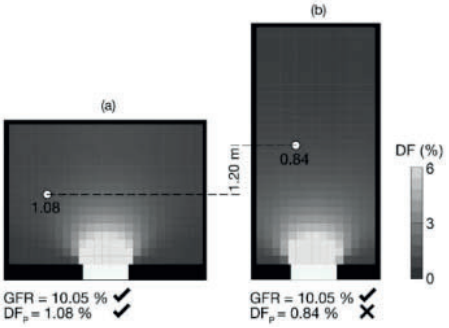


Fig. 14. A room that a) meets both criteria and b) meets only the GFR criterion. Both rooms have the same GFR (= 10.1%).

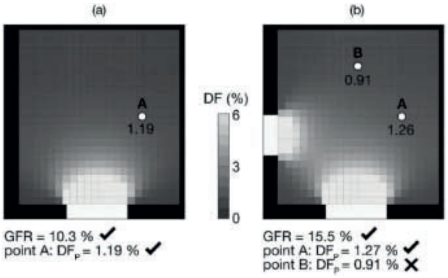


Fig. 15. a) DF_P on point A for a room with one window and b) DF_P on two possible locations for the same room as in (a) but with an extra opening. The room in Fig. 15b has more fenestration (GFR = 15.5%), but is judged as incompliant by the DF_P criterion considering point B, while the room in Fig. 15a (that has less fenestration) is judged as compliant.

criteria (GFR = 10.3%, DF_P = 1.19%). Placing a second opening on a different wall (Fig. 15b) results in two possible locations for the DF_P point, which should be placed *1 m from the darkest lateral wall*, since there are two lateral walls to be considered. Selecting the darkest of these walls would require DF_P to be calculated on point B, which results in the room not complying (DF_P = 0.91%), despite the larger fenestration (GFR = 15.5%). Effectively, a compliant room may be deemed incompliant if an extra window is added, which is counter-intuitive.

Effectively, using the GFR criterion instead of the DF_P criterion translates to using a purely geometric instead of an illuminance-based assessment, which is related to an important question: How is the assessment useful for building design? While a purely geometric assessment is useful as an early-design rule-of-thumb, it cannot be used in tandem with energy or thermal comfort assessments. Daylight simulation models may well be combined with thermal analyses in multi-objective performance studies, for early [57,58] or later [59,60] design stages, especially if they deploy climate-based daylight metrics [5,61]. This type of workflow is more in line with thinking of daylighting as suggested by Reinhart and Wienold [62], i.e. in terms of both visual and thermal objectives, with the aim to produce spaces with low overall energy use for heating, cooling and lighting. Seeing the advances of tools that are capable of performing both daylight and thermal simulations, and that practitioners in Sweden are indeed leaning towards using digital tools for daylight analyses [63], it could be argued that developing illuminance-based criteria is the way forward.

5. Conclusions

The present paper investigated building daylight regulations in Sweden to shed more light on three main questions pertaining to policy-making. Did the introduction of daylight criteria lead to an improvement of building performance historically? Is the current glazing-area assessment method applicable in residential spaces? Is there an agreement between the two assessment methods currently in force? The following may be concluded from this study:

5.1. *Daylight criteria and performance of residential spaces historically*

The answer to the first question is no; the developments built after the introduction of daylight compliance criteria are not necessarily well-performing spaces. The criteria ineffectiveness in ensuring adequate daylight levels for houses can be attributed to the fact that they have always been set as "general recommendations", not as "mandatory provisions", which means that they are not legally binding per se. Considering the financial pressure by developers who aim to increase the profitability of their investments, and the necessity to satisfy the housing demand, it would be wise to deem daylight criteria as mandatory requirements, if they are to be complied with by practitioners. After all, this is currently the way energy use criteria are safeguarded, unlike daylight criteria.

5.2. *Applicability of the GFR-method*

The answer on whether the geometry-based criterion is applicable in assessments of residential spaces is no. Three out of four rooms violated at least one geometry condition set by the GFR-method. Glazing width was the condition most commonly violated. Seeing as how newer insulated glazed units can offer less heat losses from fenestration, façade designs are expected to include wider glazing areas, which warrants a reformulation of the glazing width condition if this method is to be applicable in the future.

5.3. *Criteria agreement*

The answer on whether the two assessment methods agree is yes and no. Although the two criteria are formulated based on fundamentally different approaches, they yielded the same compliance for 87% of rooms where the GFR-method was applicable. However, in rooms where the two criteria disagreed, it was significantly more common for a room to meet the GFR-method criterion while failing the DF_P criterion. The limitations highlighted can potentially render daylight assessments prone to deliberate 'game-playing' by practitioners, who may choose one criterion over the other to achieve compliance easier, depending on the case. Furthermore, the GFR-method criterion could perhaps take into account the lower light transmittance of newer glazing types or the existence of higher obstructions, by e.g. having a higher threshold value.

Funding

This research was funded by the Swedish Energy Agency (Energimyndigheten, grant nr 41816–2), Arkus (Stiftelsen Arkus) and ARQ (c/o White Architects AB, grant nr 12:2016).

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The author would like to thank Marie-Claude Dubois for acquiring the funds for this research. Marja Lundgren and Malin Alenius are acknowledged for contributing to the building selection process.

References

[1] J. Mardaljevic, Climate-Based Daylight Modelling and its Discontents, CIBSE Technical Symposium, London (UK), 2015.

[2] A. Jacobs, Getting the measure of daylight - the climate sceptic, Light. J. (2014) 15–17.

[3] P. Tregenza, Opinion: climate-based daylight modelling or daylight factor? Light. Res. Technol. 46 (6) (2014), 618-618.

[4] P. Tregenza, J. Mardaljevic, Daylighting buildings: standards and the needs of the designer, Light. Res. Technol. 50 (1) (2018) 63–79.

[5] J. Mardaljevic, Rethinking daylighting and compliance, J. Sustain. Des. Appl. Res. 1 (3) (2013). Article 1.

[6] M. Boubekri, Daylighting, Architecture and Health: Building Design Strategies, first ed., Architectural Press, Oxford, 2008.

[7] W. Julian, Daylighting Standards, Codes and Policies, International Conference on Daylighting Technologies for Energy Efficiency in Building, Ottawa, 1998, pp. 265–269. Canada.

[8] S. Kunkel, E. Kontonasiou, A. Arcipowska, F. Mariottini, B. Atanasiou, Indoor Air Quality, Thermal Comfort and Daylight - Analysis of Residential Building Regulations in Eight EU Member States, Buildings Performance Institute Europe (BPIE), 2015, p. 100.

[9] D. Movilla Vega, D. Hallemar, 99 Years of the Housing Question in Sweden, first ed., Studentlitteratur, Lund, 2017.

[10] S. Vidén, K. Nöre, Flerbostadshusen i Sverige : kvaliteter och brister, ombyggnadsbehov och möjligheter (English: multi-dwelling buildings in Sweden: qualities and shortcomings, renovation needs and opportunities), Statens råd för byggnadsforskning (1985). Report Number: R95:1985; ISBN Number: 9154044421, http://www.byggnadsmaterial.lth.se/fileadmin/byggnadsmaterial/BFR-publ/BFR_1985-R95.pdf.

[11] Boverket, Regulatory hierarchy - from law to general recommendation. https://www.boverket.se/en/start/building-in-sweden/swedish-market/laws-and-regulations/national-regulations/regulatory-hierarchy/, 2020. (Accessed 23 September 2020).

[12] Boverket, Mandatory Provisions and General Recommendations BFS 2011:6 with Amendments up to BFS 2018:4, the Swedish National Board of Housing, Building and Planning, 2020. Karlskrona (Sweden).

[13] Kbs, BABS 1960 - Anvisningar till Byggnadsstadgan (English: Intructions for Building Regulations), Royal Building Board, Karlskrona (Sweden), 1960.

[14] Boverket, Byggregler – en historisk översikt från BABS till BBR (English: building rules - a historical overview from BABS to BBR). https://www.boverket.se/sv/byggande/uppdrag/avslutade-uppdrag/oversyn-av-boverkets-byggregler/byggregler-en-historisk-oversikt/, 2020. (Accessed 23 September 2020).

[15] Sp, Sbn 67, Svensk Byggnorm 67 (English: Swedish Building Standard), Statens Planverk (English, The National Planning Agency), Stockholm (SE), 1967.

[16] Boverket, National board of housing, building and planning. https://www.boverket.se/en/start/about/about-boverket/, 2020. (Accessed 23 September 2020).

[17] P. Rogers, M.-C. Dubois, M. Tillberg, M. Österbring, M. Alenius, I. Bournas, A. Larsson, M. Lundgren, M. Söderlund, V. Vakouli, Moderniserad dagsljusstandard

(English: modernized daylight standard), SBUF ID: 13209, http://www.bau.se/wp-content/uploads/2018/12/SBUF-13209-Slutrapport-Moderniserad-dagsljusstandard.pdf, 2018.

[18] T. Hall, S. Vidén, The Million Homes Programme: a review of the great Swedish planning project, Plann. Perspect. 20 (3) (2005) 301–328.

[19] Sp, Sbn 1975, Svensk Byggnorm (English: Swedish Building Standard), Statens Planverk (English, The National Planning Agency), Stockholm (SE), 1975.

[20] R. Marsh, On the modern history of passive solar architecture: exploring the paradox of Nordic environmental design, J. Architect. 22 (2) (2017) 225–251.

[21] M. Legnér, G. Leijonhufvud, M. Tunefalk, Energy policy and conservation planning in Sweden: a longitudinal evaluation, Int. J. Build. Pathol. Adapt. 38 (4) (2020) 555–572.

[22] B. Fritzell, H.A. Löfberg, B. Statens Institut För, Dagsljus Inomhus, Statens Institut För Byggnadsforskning1970.

[23] A.F. Dufton, Protractors for the Computation of Daylight Factors, 1946. London, UK.

[24] R.G. Hopkinson, Architectural Physics: Lighting, 1963.

[25] R.G. Hopkinson, P. Petherbridge, J. Longmore, Daylighting, Heinemann, London, 1966.

[26] Sp, Sbn, Svensk Byggnorm (English: Swedish Building Standard), Statens Planverks (English, The National Planning Agency), Stockholm (SE), 1980, 1980.

[27] Sp, Kommentarer till Svensk Byggnorm (English: Comments on Swedish Building Standard), Statens Planverks (English, The National Planning Agency), Stockholm (SE), 1980.

[28] Boverket, BFS 1988:18 - Nybyggnads Regler (English: New Building Regulations), The National Board of Housing, Building and Planning, Stockholm (SE), 1988.

[29] T. Hall, M. Rörby, Stockholm: the Making of a Metropolis, first ed., Routledge, Taylor & Francis e-Library, 2009.

[30] Swedish Sis, Standard SS 914201 - Building Design - Daylighting - Simplified Method for Checking Required Window Glass Area, Swedish Institute for Standards, 1988.

[31] Boverket, BFS 1993:57, The National Board of Housing, Building and Planning, Stockholm (SE), 1993.

[32] Boverket, BFS 2014:3, The National Board of Housing, Building and Planning, Stockholm (SE), 2014.

[33] P. Tregenza, M. Wilson, Daylighting : Architecture and Lighting Design, New York : Routledge, cop. 20112011.

[34] Cen, European Standard EN 17037:2018 Daylight in Buildings, European Committee for Standardization, Brussels (Belgium), 2018, p. 77.

[35] Kfmb, Modernare byggregler – förutsägbart, flexibelt och förenklat (English: more modern building rules - predictable, flexible and simplified). https://news.cision.com/se/kommitten-for-modernare-byggregler/r/forslag-pa-modernare-byggregler-lamnas-till-regeringen,c2994845, 2019. (Accessed 16 September 2020).

[36] Kfmb, The Building Rules Modernisation Committee, Våra Förslag - Slutbetänkande: Modernare Byggregler – Förutsägbart, Flexibelt Och Förenklat (English: Our Proposal - Final Report: More Modern Building Rules - Predictable, Flexible and Simplified), 2019, p. 438.

[37] Sbuf, Svenska Byggbranschens Utvecklingsfond (In English: Swedish construction industry development fund). https://www.sbuf.se/Om-SBUF/In-English/, 2020. (Accessed 7 December 2020).

[38] Kfmb, The Building Rules Modernisation Committee, Våra Förslag - Slutbetänkande: Modernare Byggregler – Förutsägbart, Flexibelt Och Förenklat (English: Our Proposal - Final Report: More Modern Building Rules - Predictable, Flexible and Simplified), 2019, p. 258.

[39] Ministry of Finance, Modern building rules - predictable, flexible and simplified - SOU. https://www.regeringen.se/rattsliga-dokument/statens-offentliga-utredningar/2019/12/sou-201968/#:~:text=Det%20%C3%B6vergripande%20syftet%20med%20kommitt%C3%A9ns,och%20ett%20l%C3%A5ngsiktigt%20h%C3%A5llbart%20byggande, 2019. (Accessed 7 December 2020), 68.

[40] Scb, Dwelling stock 31/12/2019. https://www.scb.se/en/finding-statistics/statistics-by-subject-area/housing-construction-and-building/housing-construction-and-conversion/dwelling-stock/, 2019. (Accessed 6 February 2020).

[41] Scb, Completed dwellings and number of rooms including kitchen in newly constructed buildings by region and type of building, Year 1975 - 2018. http://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__BO__BO0101__BO0101A/LghReHustypAr/, 2019. (Accessed 16 September 2020).

[42] C. Chatzipoulka, R. Compagnon, M. Nikolopoulou, Urban geometry and solar availability on façades and ground of real urban forms: using London as a case study, Sol. Energy 138 (2016) 53–66.

[43] B. Grünbaum, Convex Polytopes, vol. 2, Springer, cop, New York, 2003, 2003.

[44] J. Rådberg, A. Friberg, Svenska stadstyper : historik, exempel, klassificering, in: Kungliga Tekniska Högsklolan Stockholm, [Swedish City Types: History, Examples, Classification], first ed., 1996. Stockholm (Sweden).

[45] Sfs, Stadsplanelag SFS 1931:142 (English: City planning law SFS 1931:142), https://www.boverket.se/contentassets/22140678c50841128f99d542d6ab2eb7/1931-stadsplanelag.pdf, 1931. (Accessed 6 September 2020).

[46] M.L. McHugh, The Chi-square test of independence, Biochem. Med. 23 (2) (2013) 143–149.

[47] M. Elliot, I. Fairweather, W. Olsen, M. Pampaka, Cramer's v, in: A Dictionary of Social Research Methods, Oxford University Press, Online version, 2016.

[48] J. Cohen, Statistical Power Analysis for the Behavioral Sciences, second ed., Lawrence Erlbaum Associates, New York (USA), 1988.

[49] Q. McNemar, Note on the sampling error of the difference between correlated proportions or percentages, Psychometrika 12 (2) (1947) 153–157.

[50] T.J. Cleophas, A.H. Zwinderman, Clinical Data Analysis on a Pocket Calculator, in: Understanding the Scientific Methods of Statistical Reasoning and Hypothesis Testing, second ed., Springer International Publishing, Cham (Switzerland), 2016.

[51] H.B. Mann, D.R. Whitney, On a test of whether one of two random variables is stochastically larger than the other, Ann. Math. Stat. 18 (1) (1947) 50–60.

[52] H. Coolican, Research Methods and Statistics in Psychology, fifth ed., Hodder Education Group, London, United Kingdom, 2009.

[53] J.C.F. de Winter, S.D. Gosling, J. Potter, Comparing the Pearson and Spearman correlation coefficients across distributions and sample sizes: a tutorial using simulations and empirical data, Psychol. Methods 21 (3) (2016) 273–290.

[54] A. Kurvinen, A. Saari, Urban housing density and infrastructure costs, Sustainability 12 (2) (2020).

[55] Scb, Densification in half of Sweden's urban areas - statistical news from Statistics Sweden 2020-03-24. https://www.scb.se/en/finding-statistics/statistics-by-subject-area/environment/land-use/localities-and-urban-areas/pong/statistical-news/localities-and-urban-areas-2018-population-2019/, 2020. (Accessed 7 December 2020).

[56] Skr, Markpriser bostäder, In English: Land Prices, Housing), Sveriges Kommuner Och Regioner, 2020 (In English: Sweden's municipalities and regions).

[57] K. Konis, A. Gamas, K. Kensek, Passive performance and building form: an optimization framework for early-stage design support, Sol. Energy 125 (2016) 161–179.

[58] B.J. Futrell, E.C. Ozelkan, D. Brentrup, Bi-objective optimization of building enclosure design for thermal and lighting performance, Build. Environ. 92 (2015) 591–602.

[59] I. Bournas, M. Abugabbara, A. Balcerzak, M.-C. Dubois, S. Javed, Energy renovation of an office building using a holistic design approach, J. Build. Eng. 7 (2016) 194–206.

[60] H. Shen, A. Tzempelikos, Daylighting and energy analysis of private offices with automated interior roller shades, Sol. Energy 86 (2) (2012) 681–704.

[61] C.F. Reinhart, J. Mardaljevic, Z. Rogers, Dynamic daylight performance metrics for sustainable building design, Leukos 3 (1) (2006) 7–31.

[62] C.F. Reinhart, J. Wienold, The daylighting dashboard – a simulation-based design analysis for daylit spaces, Build. Environ. 46 (2011) 386–396.

[63] A. Davoodi, P. Johansson, T. Laike, M. Aries, Current Use of Lighting Simulation Tools in Sweden, 2019.

Paper 2

Paper 2

Building and Environment 150 (2019) 254–265

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Daylight regulation compliance of existing multi-family apartment blocks in Sweden

Iason Bournas*, Marie-Claude Dubois

Division of Energy and Building Design, Department of Architecture and the Built Environment, Lund University, Lund, Sweden

ARTICLE INFO

Keywords:
Daylighting
Compliance
Daylight factor
Urban density
Typology
Policy

ABSTRACT

This research investigates the daylight regulation compliance of existing multi-family housing developments located primarily in Stockholm (Lat.: 59,33 °N), Sweden. A representative sample of 54 buildings consisting of 10.888 individual rooms was modelled according to archived documentation drawings and evaluated by use of Radiance simulations, to test their compliance with the current Swedish daylight regulation. The studied buildings were selected according to their relevance to major architectural typologies of Swedish urban planning history (1926–1991). The assessment was based on a point Daylight Factor scheme (DF_P), which stipulates that a specific point in a room should achieve a Daylight Factor $DF_P \geq 1\%$, for the room to be sufficiently daylit. Results indicate that specific architectural typologies consistently yield poor DF_P levels compared to other ones. A moderate correlation was found between the density of surroundings and the percentage of compliant rooms per housing development. Finally, the results indicate the existence of distinct periods during Swedish urban planning history, when daylight performance of multi-family houses was affected by different planning practices. Future investigations are under development to evaluate the occupants' perception of daylight in their apartments, to help define new daylight performance indicators and benchmarks for Swedish households, taking into consideration the limitations of the daylight indicator embedded in the current regulation.

1. Introduction

In the last decade, a plethora of research results has emphasized the positive effects of daylighting on occupant health and well-being, including stress levels, mood, and photobiological effects [1–4]. The use of daylight has also been promoted by the International Energy Agency as a means of reducing electricity use for lighting [5]. A recent Swedish study in office buildings indicated that daylight responsive systems combined with absence detectors can yield electricity savings of approximately 50%, compared to conventional practice [6]. Other organizations promote daylighting as a strategy for resilient and biophilic building design [7]. As a result, several building codes and environmental certification systems today have some form of minimum requirements for daylighting, often expressed as a minimum window area or a minimum Daylight Factor.

More recently, Swedish urban areas have experienced drastic densification due to a steady rise in population. Boverket [8], the National Board of Housing, Building and Planning, which supervises housing from a legislative perspective, estimated in February 2016 that roughly 700.000 new households need to be built by 2025 [9]. Given this context, a research project gathering academics and experts from the industry was recently initiated with the aim to provide scientific information that will allow a reformulation of the daylight requirement in the building code, considering the necessity for sustainable urban development. The project includes four phases: a) assessment of the existing building stock by use of simulations, b) evaluation of daylight sufficiency by questionnaires to occupants, c) comparison of different performance indicators (metrics) for use in residential spaces and d) formulation of simplified guidelines for design practitioners. The objective of this paper is to present results of the first phase. These include the daylight regulation compliance of Swedish multi-family building blocks of different typologies and eras, and the impact of urban density on indoor illumination. The compliance criterion used in the analysis was the current quantified general recommendation for residential spaces, i.e. a minimum Point Daylight Factor ($DF_P \geq 1\%$) for rooms occupied more than occasionally [10].

Internationally, building standards and regulations pertaining to indoor daylight admission define minimum acceptable conditions [11], and have been shown to form mainly in three types [12,13]. The first type ensures access to sunlight, expressed as a minimum daily duration of interior insolation, e.g. at least 2 h of sunlight per day between February and October. A list of sunlight durations recommended in

---

[*] Corresponding author. Lund University, Department of Architecture and the Built Environment, P.O. Box 118, SE 22100, Lund, Sweden
E-mail address: iason.bournas@ebd.lth.se (I. Bournas).

https://doi.org/10.1016/j.buildenv.2019.01.013
Received 25 October 2018; Received in revised form 9 January 2019; Accepted 11 January 2019

different countries can be found in Ref. [14]. The second type stipulates a minimum window or glazing size, most often as a function of room area, e.g. the Greek building code [15] dictates that the window glazing area shall not be smaller than 10% of the room floor area. More such window area requirements for different EU member states can be found in Ref. [16]. The third type is formed using a minimum indoor illumination level, expressed either as a relative index, predominantly the average Daylight Factor or an absolute illuminance threshold, e.g. 300 lux, achieved for a determined room area and a particular time period throughout the year. An example of the latter is the formulation of the IES Approved Method LM-83-12 [17] or the recent European Daylight Standard EN-17037 [18]. The Swedish building code refers to a Daylight Factor approach, but unlike average Daylight Factor metrics found in other building codes or certification systems, the Swedish DF_P should be measured on a specified location within the evaluated room [19]. Eventually, all rooms within a building should have a $DF_P \geq 1\%$, for the building to be compliant.

2. Methodology

The majority of dwellings in Sweden (51%) are multi-family buildings [20], which comprise three or more apartments in the same building. They are the dominant type of housing in the largest Swedish municipalities (> 50.000 households) [21]. In Stockholm, they represent 81,1% of the total residential building stock. For the purpose of this study, a representative sample of 10.888 rooms belonging to 3.151 apartments in 54 existing buildings was selected for evaluation. Effectively, these buildings belong to 25 different housing developments located primarily in Stockholm (23 developments), and in the nearby town of Örebro (2 developments). The selection of the evaluated buildings was based on two criteria: a) the year of construction and b) the building typology.

2.1. Selection based on construction year

Following the first criterion, the selection was made according to the frequency of constructed apartments per decade, focusing on the 20th century. A total of 2.192.385 apartments were registered in Sweden until 2000, according to the national statistics agency [22]. Out of this stock, 3.151 apartments were selected for evaluation. The amount of selected apartments per decade was determined by the actual building rate that occurred during each decade. In other words, the ratio of evaluated apartments belonging to one decade (percentage of 3.151) corresponded to the ratio of apartments built during that decade (percentage of 2.192.385). The reason for this analogy was the intent to draw conclusions for the overall building stock.

2.2. Selection based on building typology

Following the second criterion, the buildings were selected according to their relevance to major architectural typologies adopted in Swedish urban planning history. Practicing urban planners and architects specialized on residential spaces were consulted in a reference group to determine this aspect. The eventual selection was made in accordance with the categorization of Swedish urban typologies as described in Rådberg and Friberg [23], which are in line with the typologies described earlier by Hall [24]. Fig. 1 shows the eight main typologies that were studied (one typology per row). Following is a short description of each type:

- *Low-rise towers* ("låga punkthusgrupper") have a concentrated plan and a central stairwell, with typically four apartment units built around it. They are three to four stories high, and may have rooms with windows on two directions.
- *High-rise towers* ("höga punkthusgrupper") have a plan layout similar to their lower counterparts, but can reach as high as 16 stories. They were developed mainly in peripheral zones of the city, to accommodate a significant amount of apartments and still provide ventilation and daylight for most rooms. They represented the modernist ideal image of the "house in the park" [23].
- *High + Low combination* of tower and narrow building types were adopted with the intent to extract the advantages of both types. The low part could provide sufficient ventilation and daylight for most rooms, but with less apartments per stairwell. The high part would contribute with its housing capacity, and provide a dramatic elevation profile.
- *High-rise enlongated* ("skivhusgrupper") buildings have at least 50 m length, and usually three to four stairwells. They succeeded the high-rise towers as the main high-rise building type, when prefabrication became common (after 1960), and were used to accommodate high numbers of apartments in the same building.
- *Exterior circulation* ("loftgånghus") were typically used between 1965 and 1974 under the Million Homes Programme [25], to allocate elevator costs to a larger number of apartments, by providing apartment entrances through shared external corridors.
- *Semi-open courtyard* blocks were built primarily in the 1940s and 1950s, in suburban areas, and were typically three stories high. They are the result of the transition from the 1930s linear narrow buildings to formations of narrow buildings that would create semi-open, private courtyards. The building volumes were as narrow as 8 m.
- *Large courtyard blocks* emerged from the 1907 Town Planning Act [26] that granted Stockholm's municipality the power to ban building volumes within courtyards, which was the usual practice earlier. They became common in metropolitan inner parts as a "reform", which comprised a uniformly designed block of buildings that surrounded a large, park-like, inner courtyard [24].
- *Post-modern reforms* are the result of the intent after 1975 to adopt older block types (prior to 1930), but with a more blurred limit between the street and the private courtyard, along with higher building masses.

In Fig. 1, codes A to Y correspond to the 25 individual developments, some of which consist of more than one building. At least three developments per typology were included in the sample. The left-hand side of the figure (grey background) shows the surrounding zone for each development, in a range of 250 m. The simulated buildings are shown in red footprints. The surrounding zone was defined as a function of the area occupied by the evaluated buildings. The algorithm for this is described further down. On the right-hand side, the development footprints are shown on a larger scale, along with data regarding their surrounding zones. Different zones are characterized by different urban densities and building heights. Below each footprint, three indicators are presented:

- *Density* [m^3/m^2]. Urban density expresses the magnitude of the total built volume [m^3] per site area [m^2]. It has been proven to correlate strongly with the available irradiance on building facades of real urban developments [27].
- *Building height* [m]. For this study, building height (H) refers to the evaluated development and is measured from the lowest point of the adjacent street to the upper-most point of the exterior wall (i.e. inclined roofs are not considered). In cases where the development comprises buildings of different heights, the average height is shown, denoted by "*". This height is weighted by footprint area of the differing buildings.
- *Mean Building Height* [m]. Mean Building Height (MeH) is calculated as the mean height of all buildings in the zone, weighted by their footprint area. It expresses the verticality of a given site area, the extent to which building masses elevate from the ground.

Table 1 shows aggregated data of the selected building sample,

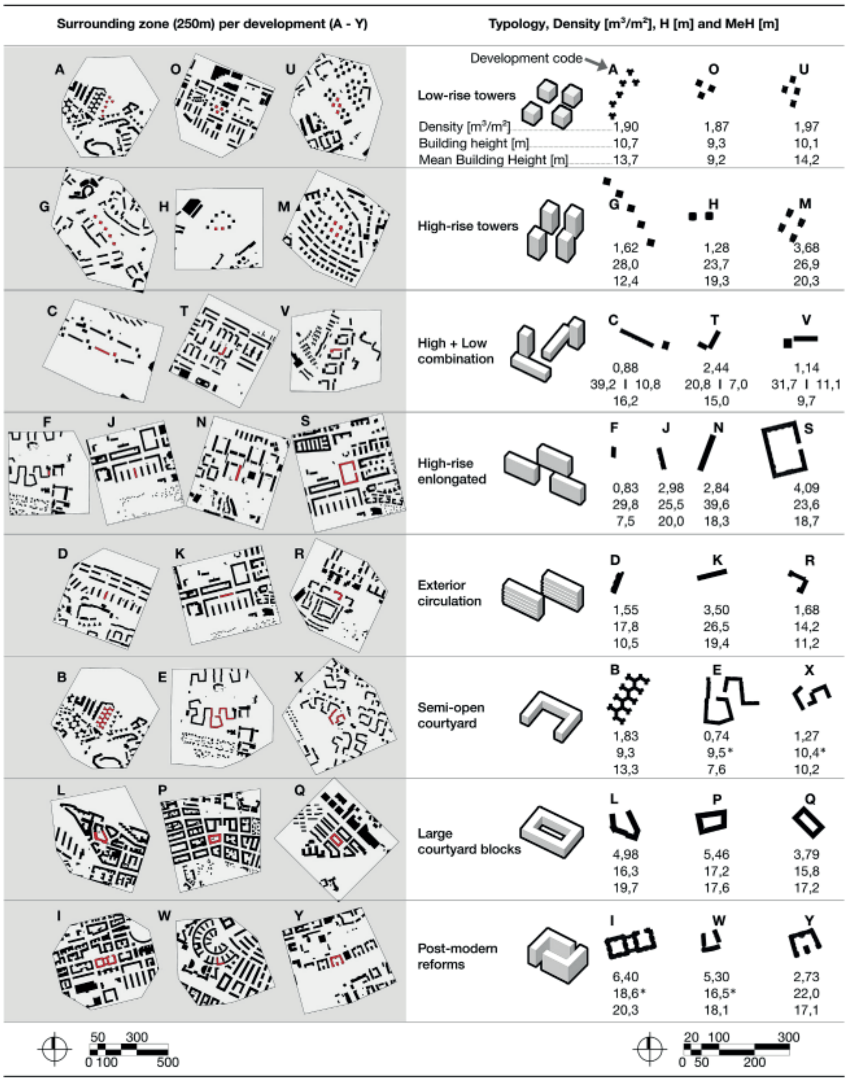


Fig. 1. Categorization of the 25 evaluated developments in eight main typologies according to Ref. [23], their urban zones, footprints and urban indicators of Density, Building height (H) and Mean Building Height (MeH).

sorted by construction year from top to bottom row. Codes A – Y correspond to individual developments, and numbers 1 to 54 to individual buildings. A development may comprise more than one buildings (e.g. M consists of buildings 29, 30, 31 and 32). The number of rooms per building is shown in grey fill, and it indicates the architectural typology of a development. As explained previously in sections 2.1 and 2.2, the aim was for the sample to include buildings of different construction eras (criterion 1), and different typologies (criterion 2). The amount of apartments per decade (compared to 3.151) corresponds to the real construction rate that occurred historically.

Table 1
Aggregated data of building sample, including decade of construction, nr of apartments and rooms per building, development and typology.

Decade	Development Code	BuildingCode	Nr of apartments	Nr of apartments per decade	Nr of rooms per building and typology							
					Low-rise towers	High-rise towers	High + Low combination	High-rise enlongated	Exterior circulation	Semi-open courtyard	Large courtyard blocks	Post-modern reforms
1921–1930	Q	38	167	650							**381**	
	L	28	232								**541**	
	P	37	251								**613**	
1931–1940	M	29	64	256		**224**						
		30	64			**224**						
		31	64			**224**						
		32	64			**224**						
1941–1950	H	23	38	292		**136**						
		24	38			**136**						
	A	1	9		**33**							
		2	9		**33**							
		3	9		**33**							
		4	9		**33**							
		5	9		**33**							
		6	9		**33**							
	B	7	162							**486**		
1951–1960	X	51	33	623						**105**		
		52	18							**72**		
		53	57							**162**		
	E	11	21							**75**		
		12	8							**29**		
	F	14	40					**112**				
	E	15	8							**29**		
		16	18							**64**		
		13	12							**54**		
		17	61							**228**		
	V	47	50				**180**					
		48	18				**78**					
	G	18	39			**148**						
		19	39			**148**						
		20	39			**148**						
		21	39			**148**						
		22	39			**148**						
	C	8	48				**240**					
		9	36				**168**					
1961–1970	S	40	309	675				**1408**				
	O	34	9		**32**							
		35	9		**32**							
		36	9		**32**							
	T	41	36				**174**					
		42	4				**24**					
	U	43	12		**59**							
		44	12		**59**							
		45	12		**59**							
		46	12		**59**							
	D	10	30						**125**			
	N	33	221					**878**				
1971–1980	J	26	43	187				**273**				
	K	27	88						**277**			
	R	39	56						**216**			
1981–1990	I	25	230	230								**801**
1991–2000	W	49	91	238								**124**
		50	17									**63**
	Y	54	130									**470**
			TOTAL:	**3151**	**530**	**1908**	**864**	**2671**	**618**	**1304**	**1535**	**1458**

2.3. Modelling and simulation settings

For each development, the simulation model included a) the surrounding buildings, b) the evaluated buildings and c) the terrain geometry. Tree geometries were not modelled, and the terrain was assumed uniform (no distinction between different materials/vegetation).

Surrounding buildings for each development were retrieved from three-dimensional vector data of Stockholm city [28], which were imported from ArcGIS ArcMap [29] to Rhinoceros 3D [30]. The imported data were further processed using the visual programming editor of

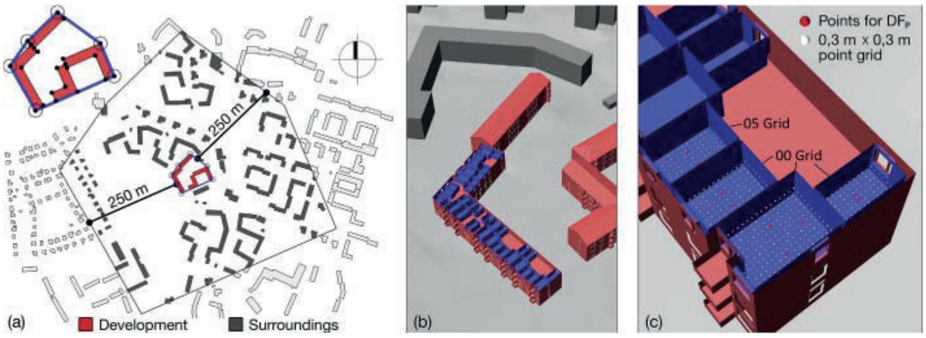


Fig. 2. a) Considered surroundings (dark grey footprints) within the 250 m offset of the convex hull (blue polyline), b) perspective view of part of development X and c) The DF_P points (red spheres), the 0,3 × 0,3 grid points (white spheres) and the distinction between the 00 Grid and the 05 Grid. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Grasshopper [31] to cull the desired surroundings according to Fig. 2a. For a given development, the footprint perimeter vertices (black dots in Fig. 2a) were used to compute a planar convex hull (blue line in Fig. 2a). A convex hull for a point set S in the Euclidean space is the smallest convex set containing S [32]. The points on the convex hull are circled in Fig. 2a. The hull was offset by 250 m to construct a boundary polyline. All buildings (or subparts of buildings) within this boundary polyline were included in the simulations (dark grey footprints), and in the calculations of the urban indicators described previously in section 2.2. This approach ensures a minimum extent (250 m) of surroundings from all outward facing façades of a development. The particular method was conceived for the current study, as there is no normative method to define surroundings for daylight simulations. The extent of 250 m was selected to achieve a spatial scale of roughly 500 × 500 urban cells, which is similar to spatial scales used in studies dealing with urban forms and solar availability [27,33]. It also ensures that most visible surroundings are accounted for, as many developments of this study are located in zones of low urban density (e.g. development X in Fig. 2a).

The evaluated building facades and interior plans were retrieved from available documentation drawings, in raster or pdf format, from Stockholm City Planning Office [34]. Following the current Swedish building recommendation [10], the room types designed and evaluated were the ones occupied more than occasionally: kitchens, living rooms, bedrooms and dining rooms. Fig. 2b shows the distribution of these rooms across part of the third floor of development X. For each room, the a) point Daylight Factor (DF_P) and b) the average and median Daylight Factors (DF_A and DF_M) were calculated for different sensor points, evaluated during the same simulation run. DF_P was calculated on specific points (red spheres in Fig. 2c), while DF_A and DF_M were deducted from calculations on a point grid of 0,03 m spacing (white spheres in Fig. 2c). The DF_P was calculated according to definition, on a point *located halfway through the room depth, one meter from the darkest lateral wall, 0,80 m above floor level.* Locating that DF_P point is not straightforward, as the definition of the *darkest lateral wall* is only based on intuition, in the absence of simulation results. Moreover, the *room depth* is an ambiguous measure in cases of non-rectangular room layouts or in cases where it can be confused with room width (e.g. differently oriented facades, as in the corner room of Fig. 2c). For these reasons, all possible DF_P sensor points (depending on room geometry) were evaluated, and the value of the least illuminated point was reported as the DF_P. The DF_A and DF_M were calculated for the overall room area (00 Grid in Fig. 2c) and for the area offset 0,50 m from walls (05 Grid in Fig. 2c). The corresponding metrics are denoted as DF_A00, DF_M00 and DF_A05, DF_M05 in the results section. Sensor points were set 0,80 m above floor level.

The terrain geometry was modelled using the digital elevation model (2 m resolution DEM) available from the Swedish Surveying and Cadastral Agency [35]. The raster image was exported from ArcGIS ArcMap to Grasshopper to construct a Delaunay mesh from xyz coordinate points, for use in the Radiance simulation model, to the same spatial extent as the surroundings.

Radiance [36] was the daylight simulation engine used, via the Honeybee plugin [37] that is deployable within the visual programming environment of Grasshopper [31]. Radiance is a backward ray-tracer that uses a hybrid Monte Carlo (stochastic) and deterministic raytracing approach to model both direct and indirect light contributions accurately. It has been rigorously validated in the past [38–42] and has shown good agreement with illuminance measurements in full-scale spaces, with inaccuracies ranging between ± 10% [43]. The Radiance rendering settings used are shown in Table 2. The only parameter varying per development was the ambient resolution (ar), which was set equal to $(D_{MAX} \cdot 0{,}1)/0{,}03$, where D_{MAX} is the maximum scene size of the development zone in m. The minimum separation for cached irradiances was therefore always set to 0,03 m, which was the minimum dimension used in the geometrical models (i.e. the window frame size).

2.3.1. Geometry details and optical properties

Geometry was modelled with a 0,05 m tolerance for all surfaces except window frames. The frames were designed with a 0,03 m tolerance, positioned on the wall as stated in the documentation drawings. Balcony railings were modelled as transparent surfaces, with a visual

Table 2
Radiance simulation parameters.

ambient bounces	ab	7
ambient divisions	ad	2048
ambient supersamples	as	512
ambient accuracy	aa	0,1
ambient resolution	ar	variable
ambient value	av	0
limit weight	lw	0,0001
limit reflection	lr	7
direct threshold	dt	0,03
direct certainty	dc	1
direct subsampling	ds	0,05
direct jittering	dj	0,7

Table 3
Surface optical properties.

Surface type	Reflectance*	T_{VIS}
Walls (interior), closets	70%	–
Ceiling	80%	–
Floor	30%	–
Window glass	–	70%
Window frame	80%	–
Window head, jamb & sill	50%	–
Balcony ceiling	70%	–
Balcony floor	30%	–
Ground	20%	–
Surrounding buildings trees	30%	–
Roofs	30%	–
Water	50%	–
Railing (as planar glass surface)	–	variable

*Overall reflectance (red, green, blue).

transmittance (T_{VIS}) computed according to the amount of railing pillars; a 50% pillar coverage ratio on the railing façade was translated to a 50% visual transmittance for the Radiance "glass" primitive used. No furniture was modelled, apart from closets embedded in walls, most often found in bedrooms.

For all 10.888 evaluated rooms of this study, a standard set of optical properties was assumed, according to recommended reflectance values [17,44,45], shown in (Table 3). All opaque surfaces were modelled as Lambertian diffusers by use of the Radiance "plastic" primitive, with roughness and specularity set to zero. No colour was assumed for the surfaces; RGB coordinates were equal. Glazing T_{VIS} was assumed 70% for all models, which represents fairly a double-pane window. Balconies floors and ceilings were designed as having different finishes, the latter being brighter. Some developments were located in areas adjacent to the canals of Stockholm city. For these cases, the water surface was modelled as a planar surface with 50% visual reflectance.

It should be noted here that buildings of certain eras have undergone renovations during their lifetime, to improve their energy performance and thermal comfort, e.g. development V is undergoing energy renovations under a Horizon2020 funded European project [46]. Changes due to such renovations are not accounted for in this study, as the buildings were modelled according to their original plans. Measures such as the replacement of older windows with highly insulated units or the addition of glazing to balconies can reduce indoor illuminance even further. The same is true for furniture, which was not modelled for this study. Furniture has been shown to decrease daylight illuminance significantly, particularly for points located deeper in a room [47]. To a certain extent, the results presented here are on the optimistic side of the actual daylight performance of the evaluated developments.

2.3.2. Amendments to the current calculation method

Due to the previously stated ambiguity (section 2.3) introduced by the definition of the point location of the DF_P measurement, we evaluated the correlation of the point measurement with the different daylight metrics described under section 2.3 (DF_A00, DF_A05, DF_M00 and DF_M05). The DF_P was also correlated to the percentage of room area for which the Daylight Factor was higher than 2% (%Area2). Same as the DF_P, these metrics are also based on the Daylight Factor scheme. They can be calculated for a grid of points on the horizontal plane and require no different simulation technique than the DF_P requires. The correlation of the metrics with typical room measurements was also tested, in particular with the room depth (Depth), width (Width), floor area (FloorA), window-to-floor ratio including frames (WFR) and the area of the external wall of the room (EWA), measured from outdoors. The significance of the correlation between all variables was high, due to the large sample of evaluated rooms (n = 10.888).

3. Results

3.1. Compliance of evaluated building stock

This section presents the degree of compliance of the evaluated building sample, according to the current $DF_P \geq 1\%$ general recommendation. According to the latter, all rooms occupied more than occasionally within a building need to comply, for the building to be considered compliant. Effectively, even if only one room is not compliant, the building cannot comply. In this study, the percentage of compliant rooms within different levels (building, development and typology) are presented separately, to indicate performance per level.

Fig. 3 shows the DF_P obtained for each room in each of the 54 studied buildings. The buildings are grouped in developments (codes A – Y) and sorted per typology. The DF_P threshold of 1% is denoted by the vertical grey line. When all rooms in a building comply with the current recommendation, the building code is shown in bold characters on the y-axis, for clarity. If we rank the DF_P of all rooms within a building (circular markers), we can derive the median score, which is shown in a linear marker. Consequently, when the linear marker lies below the $DF_P = 1\%$ threshold, it indicates that the majority of rooms in that building fail to comply with the requirement (red linear marker). The corresponding building code is shown in red to highlight the darkest cases. Out of the 54 buildings, 14 were found compliant (26%). These buildings belong mainly to the "Semi-open courtyard" typology and the typologies using concentrated plans, the "High-rise towers" and "Low-rise towers". Two additional buildings were found compliant (building 8 of development C, and building 14, which is development F); these two belong to other typologies, and were found compliant for reasons pertaining to their surroundings. Both of them are built in low density zones (0,88 and 0,83 m^3/m^2 respectively), and their height has the highest deviation from the average building height of their zones (Fig. 1). In other words, these buildings are considerably higher than their surroundings, which are characterized by both low density and low heights. Developments that consist of high-rise buildings (e.g. M, T, J, S) exhibit a broader room DF_P range, indicating a gradual increase of illumination from lower to higher floor levels. A high range is also an indicator of large deviations in design between room types of the same building. For instance, development U comprises of low towers (three stories) compared to development G (ten-stories), but has a higher DF_P range due to the uneven distribution of daylight within its apartments (windowless kitchens, brighter living rooms).

For most buildings (47 out of 54 buildings), the majority of rooms achieve a $DF_P \geq 1\%$ (median marker $\geq 1\%$), but a significant amount of rooms per building fall below what is considered adequate. Of all the 10.888 evaluated rooms, 3.428 did not pass the $DF_P \geq 1\%$ benchmark (32% of the rooms). For some buildings (e.g. 23–24), the non-compliant rooms were simply windowless rooms, mainly kitchen rooms, located in the core of the building; the vast majority of windowless rooms (96%) did not fulfill the requirement.

Examining the performance in the development level (codes A – Y), it is evident that buildings of the same development (and thus the same urban zone) have similar compliance rates (e.g. buildings 18–22, 29–32, 34–36). The standard deviation of the compliance rate of buildings in the same development ranged between 0 and 5,5%. Due to this similarity, the following results are presented per development category. There are only two exceptions: The compliance rates of buildings in developments C and W differ by 18% and 30% respectively. These deviations are attributed to significant differences in building height, room depth, width and window-to-floor ratio (WFR) that will not be analyzed in this paper.

The percentage of complying rooms ($DF_P \geq 1\%$) per development (codes A – Y) is shown in Fig. 4. The developments are grouped in their respective typologies, which are sorted from best to worst performing ones (from left to right). The compliance rate per typology is indicated at the bottom of the figure, in bold characters, next to each typology

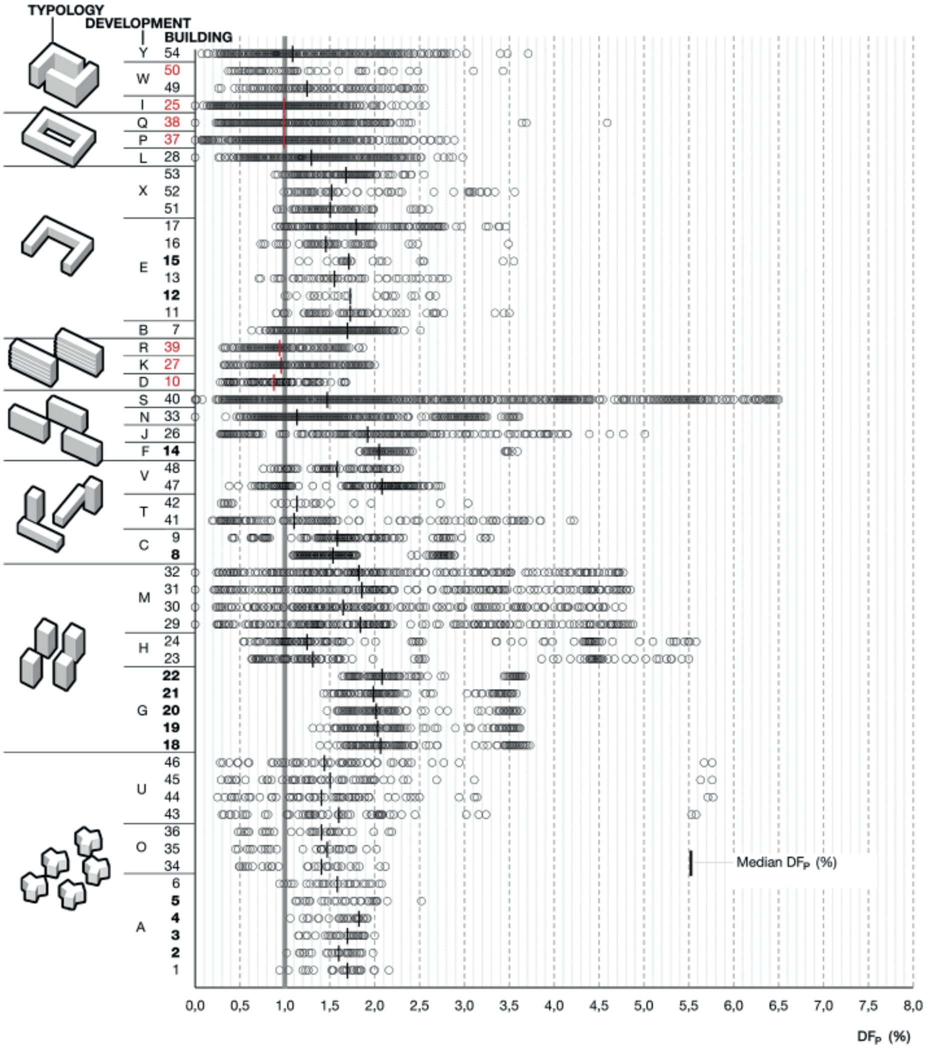


Fig. 3. DF$_P$ obtained for all 10.888 simulated rooms. The results are categorized in eight (8) typologies, 25 developments and 54 buildings. The median DF$_P$ of all rooms per building is denoted with a linear marker.

thumbnail. The numbers in circles correspond to the urban density (m^3/m^2) for each development zone. Developments with more than 95% compliant rooms are shown in green bars. Observing the performance of different typologies, it is evident that “Exterior circulation” exhibits the poorest performance (only 40% of rooms comply for this typology). Buildings of this type have the highest amount of rooms with access to a balcony or an external corridor (55%–68% of rooms, depending on building). For these rooms, the sky exposure is reduced significantly, and illumination is only available from reflected light (from surroundings) or from the lower parts of the sky. The latter provides lower luminance compared to the higher parts of the sky, due to the CIE Overcast Sky luminance distribution. The “Large courtyard blocks” and

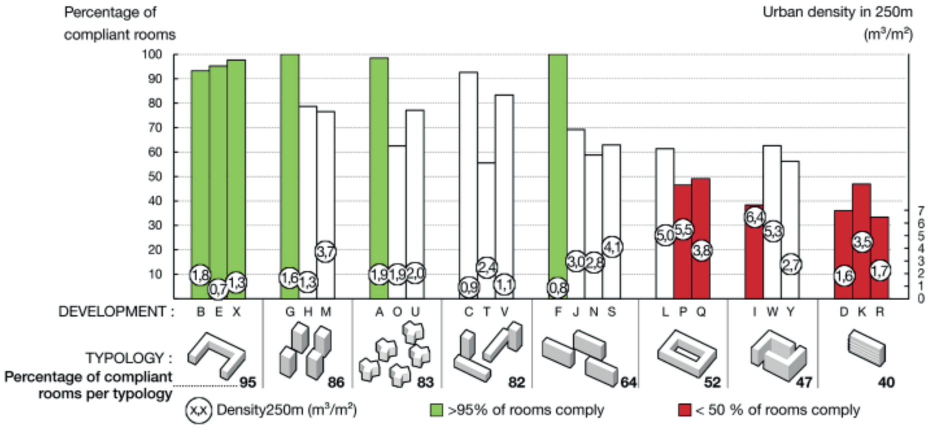


Fig. 4. Percentage of compliant rooms ($DF_P \geq 1\%$) per development (A–Y) and urban density (m^3/m^2) in 250 m.

"Post-modern reforms" also exhibited low amounts of compliant rooms (52% and 47% respectively). Buildings of these typologies are built in the densest urban zones considered in this study, with urban densities reaching up to 6,40 m^3/m^2.

Among the better performing typologies, the "Semi-open courtyard" (B, E, X) clearly stand out (95% of rooms have $DF_P \geq 1\%$). The "High-rise towers" (G, H, M), "Low-rise towers" (A, O, U) and "High + Low combination" (C, T, V) are ensuring similar amounts of complying rooms (between 82% and 86%). Observing the urban density indicator, it is evident that the best performing developments (green bars: B, E, X, G, A, F) are built in zones of low urban density (ranging from 0,7 to 1,9 m^3/m^2).

To facilitate reading the results outside the Swedish national regulation perspective, Fig. 5 shows the compliance per development (codes A – Y) using the commonly used $DF_A05 \geq 2\%$ criterion, which is also founded on the daylight factor basis. A room is considered compliant when the average Daylight Factor is at least 2% for the room area excluding a 0.5 m perimeter gap. The particular criterion is used here due to its common use among practitioners internationally rather than its reliability as a performance indicator. The compliance rates shown in Fig. 5 are lower for all developments and the typologies rank differently compared to Fig. 4. The reduction in compliance for each typology in shown at the bottom of Fig. 5, in grey font. The general reduction among all typologies can be attributed to the different benchmark values between the two criteria ($DF_P \geq 1\%$, $DF_A05 \geq 2\%$). For developments that achieved very high daylight factors (A, F, G in Fig. 3), the switch from DF_P to DF_A05 does not affect compliance. The "Large courtyard blocks", "Post-modern reforms" and "Exterior circulation" show a distinctly lower performance compared to the rest of the typology types, just as with the DF_P criterion. According to DF_A05, the best performing typology is the "High-rise towers" type. The highest reduction of compliance when switching from the $DF_P \geq 1\%$ criterion

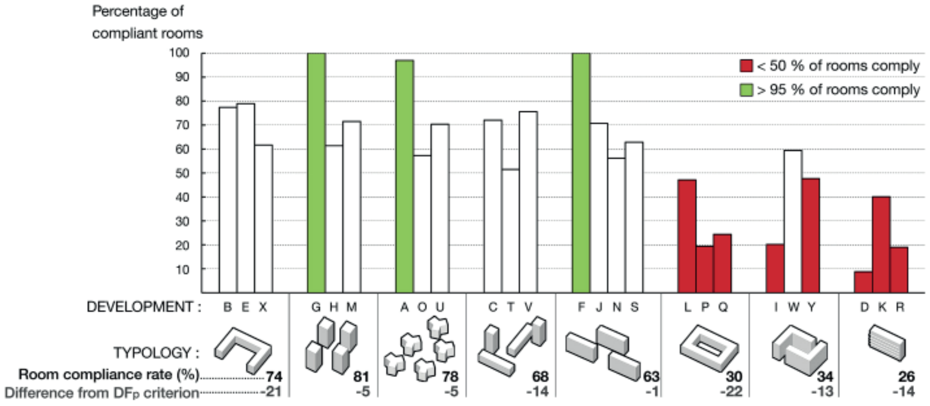


Fig. 5. Percentage of compliant rooms (DFavg05 ≥ 2%) per development (A–Y).

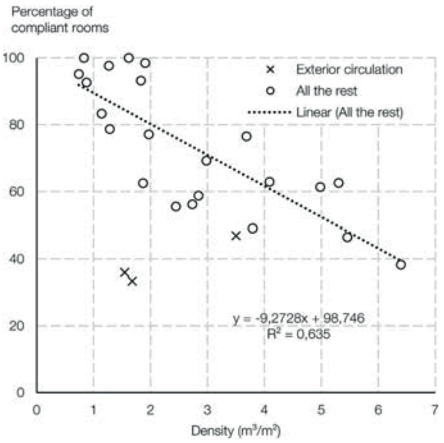


Fig. 6. Linear regression model for percentage of compliant rooms (per development) and urban density.

to the $DF_{A}05 \geq 2\%$ criterion is found for the "Semi-open courtyard" and the "Large courtyard blocks" typologies (−21% and −22% less compliant rooms).

The authors are aware of the fact that the urban density indicator cannot be the sole determinant of daylight performance of indoor spaces. The linear regression model of urban density and percentage of compliant rooms (according to DFp) is shown in Fig. 6. The "Exterior circulation" developments (cross markers) are not included in the model, as balconies deem the impact of surroundings less important, due to self-shading. Approximately 64% of the variance in the compliance rate can be explained by the density indicator. This leaves 36% of the compliance variability still to be accounted for by other parameters, which pertain to interior room geometry (e.g. room depth, width, window size). An analysis of these parameters will be presented in a separate article. In this study, there were four poorly illuminated developments built in urban zones of relatively low densities ($< 3,0\,m^3/m^2$). These were developments N, O, T, Y. Developments N and O (densities = 2,84 and 1,87 m^3/m^2 respectively) have deep rooms with low window-to-floor ratios (WFR), compared to other developments. Development T (density = 2,44 m^3/m^2) has the second highest rate of windowless rooms (20% of rooms) and the second lowest WFR. Development Y (density = 2,73%) is the highest of all closed courtyard-type developments, at 22,0 m height (Fig. 1), causing considerable self-shading for the rooms facing its courtyard, particularly the ones located in lower floors.

3.2. Policy implications

Fig. 7 illustrates all developments and their corresponding building footprints, sorted according to their construction year. Each of the 54 buildings is coloured according to its compliance rate (percentage of rooms where $DF_P \geq 1\%$). The number of buildings per year is shown on the timeline. The range of urban density for different decades [m^3/m^2] is shown below the timeline. The figure indicates that the best performing buildings of this sample were constructed between 1940 and 1960, creating urban zones with an urban density ranging from 0,74 to 1,62 m^3/m^2, which is the lowest range among all decades. Buildings before 1930 and after 1980 exhibited the poorest performance, and the highest urban densities.

The results presented in Fig. 7 become more meaningful when considered in conjunction with prevailing planning practices during four distinct periods of Swedish urban planning history. Prior to 1930, the urban practice of using enclosed courtyards to define strict urban grids led to opposite facades in close proximity with each other (Fig. 1, developments L, P, Q). This resulted in higher densities and consequent low daylight levels (Fig. 7). The Swedish functionalism that prevailed after 1930 prioritized healthy living, natural ventilation and daylight for houses [48], primarily with the use of narrow building volumes. Thicker buildings were banned in the suburbs of Stockholm, with few exceptions [24]. Expansion of the city was manifested through multi-family buildings with less apartments per stairwell (developments E, X) or, to build more apartments, more tower typologies (developments G, H) and combinations of tower and narrow typologies (developments V, C) [24]. All such choices provided windows for most rooms, providing adequate daylight. The year 1961 was a turning point. During the "record years" [25] between 1961 and 1974, the housing crisis led to an unprecedented rate of new constructions, and government policies such as the Million Homes Programme [25] came to force. Encouragement for more apartments per building led to higher buildings with deeper plans and larger apartments to accommodate larger families. Those apartments comprised more rooms placed closer to the building core (developments S, J, T, U). Moreover, solutions to reduce construction costs included "Exterior circulation" types (developments D, K, R), that were used to reduce circulation costs (including heating), all while causing self-shading. Overall, the norms followed between 1961 and 1974 led to lower daylight utilization, compared to the preceding era, as indicated by Fig. 7. The last quarter-century period also exhibits poor performance. Stockholm did not experience suburbanization in the scale of the 1960s, but made a crucial transition in its urban planning history: the shift from expansion to densification. Planning tendencies focused on more central areas and created blocks similar to the 1930s courtyard blocks (developments I, Y) but this time using higher building volumes. Urban density and self-shading resulted in a higher amount of non-compliant rooms, just as in the pre-1930s era.

3.3. Amendments to the current calculation method

An amendment to the current calculation method is necessary to remove the ambiguity of the DF_P point location, as explained in section 2.3. A grid-based approach could eliminate the issue of having to locate the correct position for the calculation point. Pearson correlation analysis (two-tailed) was performed to test the relationship between the DF_P metric and grid-based metrics of the daylight factor base. Table 4 shows the bivariate coefficients for the evaluated variables, which also included typical room dimensions. The Median Daylight Factor of the area excluding 0,50 m from the room perimeter ($DF_{M}05$) exhibits the highest correlation with the DF_P (r = 0,979; n = 10.888). This was expected, as the median measurement should approximately coincide with the illumination in the central part of a room, where the DF_P point is located. In correlating with DF_P (bold characters in Table 4), the superiority of the median to the average measurement is indicated by the higher Pearson coefficients, and can be attributed to the fact that the median is not affected by extreme values (high or low extremes). Extreme values are also discarded when the 0,50 m perimeter area is excluded (direct skylight from window, dark corners at the back of the rooms). This is evident if one compares the coefficients (in bold) between $DF_{A}00$ and $DF_{A}05$, and between $DF_{M}00$ and $DF_{M}05$. The percentage of area where the Daylight Factor is higher than 2% (%Area2) correlates strongly with the average metrics ($DF_{A}00$, $DF_{A}05$), as shown in previous research [49]. However, the strongest correlation is observed between DF_P and $DF_{M}00$ (r = 0,963).

Regarding the typical room dimensions, the correlation between WFR and each daylight metric is moderately strong (r > 0.6). The room Depth is negatively correlated with the metrics as expected; its highest correlation is with DF_P and $DF_{M}05$. However, causation needs

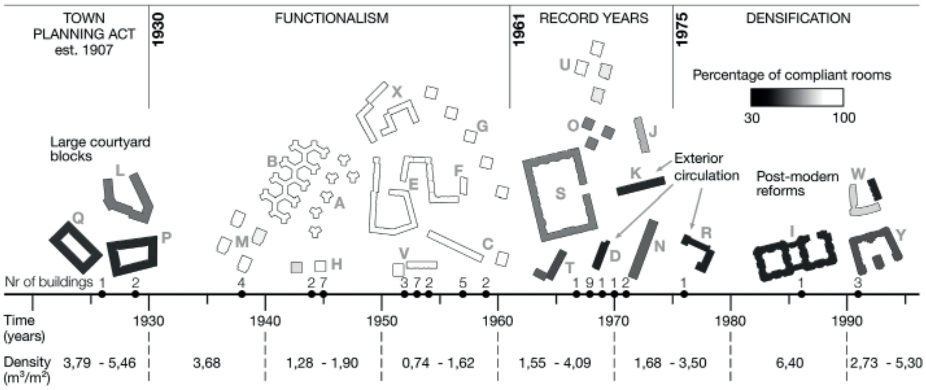


Fig. 7. Building footprints coloured according to percentage of compliant rooms ($DF_P \geq 1\%$) and sorted according to construction year.

to be investigated further, factoring the impact of surroundings and more room geometrical characteristics.

4. Discussion

Most investigations on daylight performance have previously focused on non-residential premises, especially offices. For residential spaces, daylight studies usually evaluate specific rooms, apartments or buildings [50]. Overall evaluations on the urban block level are scarce [51,52], and typically deploy a methodological approach that defines generic building forms [53], most often with fixed geometric parameters (e.g. fixed window-to-wall ratios). The present study evaluates existing apartment blocks and argues that the distinction from generic forms is important for the assessment of daylight potential. In most European cities with a history of urban developments, it is rare that entire urban zones are developed by repeating the same building type. The inhomogeneity of surrounding volumes in most real-case scenarios is high, and arrays of new buildings are not always symmetrical to a single axis.

The relationship of building form with indoor illumination is not as straightforward as it is with irradiation on external facades [27], deeming urban indicators inadequate for a complete daylight prediction. Individual characteristics that pertain to interior layout (e.g. room distribution, room depths) are most often dependent on specific design choices, relevant to policies and architectural trends. For instance, the importance of urban density in the present study was offset for buildings with higher usage of balconies ("Exterior circulation" typology). The urban density was also no clear indicator of daylighting for cases such as development T, where the apartment room distribution was found to dictate the compliance rate, instead of the low urban density (2,44 m^3/m^2). In fact, the architectural plan of development T resulted in one out of five rooms being windowless (one room per apartment). Other parameters pertaining to room geometry, such as window size and position, room depth and plan shape can also affect daylight illumination. Such variables were not analyzed in this study, and should be of main interest in future investigations. Nevertheless, as demonstrated by the findings, specific building types perform consistently better than others do (e.g. "Semi-open Courtyards").

Reflecting on the research, there are aspects of policy-making that we can highlight. Testing compliance with the current DF_P recommendation of the Swedish building code [10] showed that 40 out of the 54 evaluated buildings (74%) failed to comply. Given the densification process currently under way, it is reasonable to assume that the building industry will not follow the recommendation as it is currently formulated, unless it becomes a binding requirement. In case of a binding requirement, the authors believe it will need to be reformulated, accounting for the occupants' perception of daylight in their apartments. Moreover, the current DF_P metric carries with it all the limitations of a Daylight Factor based metric. It does not consider daylight design parameters such as latitude, orientation, time and climatic conditions. Compliance methods have been reviewed in the past [54] and there is research evidence to support the transition to climate-based performance indicators. In the meantime, the high correlation found between DF_P and DF_M05 implies that altering the current regulation for a grid-based metric could be a temporary solution. This change can remove the current ambiguity in determining the

Table 4
Pearson Correlation (2-tail) for different daylight metrics and room characteristics, n = 10.888.

	DF_P	DF_M00	DF_M05	DF_A00	DF_A05	%Area2	FloorA	EWA	WFR	Depth	Width
DF_P		**0,959**	**0979**	**0,888**	**0939**	**0,904**	−0,288	0092	0,633	−0,386	−0,131
DF_M00			0,976	0946	0,964	0963	−0,173	0203	0,679	−0,291	−0,041
DF_M05				0,912	0963	0,933	−0,242	0182	0,661	−0,376	−0,064
DF_A00					0,971	0960	−0,033	0293	0,658	−0,114	0037
DF_A05						0,953	−0,107	0265	0,656	−0,214	0013
%Area2							−0,180	0193	0,666	−0,293	−0,081
FloorA								0,567	−0,068	0832	0,745
EWA									0,236	0331	0,610
WFR										−0,155	0063
Depth											0,398
Width											

measurement point, and introduces a grid-based approach that can be developed further, according to climate-based indicators defined by future research.

5. Conclusions

We have investigated the compliance of Swedish multi-family housing developments with the $DF_P \geq 1\%$ recommendation of the current building code. The results were informative of the impact of urban density and choice of architectural typology. In addition, we have demonstrated that distinct periods can be defined during Swedish urban planning history, when different planning practices of the 20th century affected daylight admittance for multi-family blocks. Eventually, we proposed a temporary reformulation of the current building code that removes ambiguity in the evaluation method, and that could start a dialog in Sweden about a reformulation towards climate-based indicators in the years to come.

5.1. Compliance rate and typologies

Out of 54 evaluated buildings, only 14 were found compliant with the current recommendation (26%), which is a low compliance rate. The building typologies that exhibited the highest rates were the "Semi-open courtyard", followed by "High-rise towers", "Low-rise towers" and the "High + Low combination" (95%, 86%, 83% and 82% of rooms, respectively). The least illuminated developments belonged to typologies of "Exterior circulation" (40%), followed by "Post-modern reforms" (47%) and "Large courtyard blocks" (52%). The performance for each typology was shown to depend significantly on surrounding obstructions.

5.2. Compliance rate and density

The urban density [m^3/m^2] indicator was found to correlate moderately ($R^2 = 0{,}635$) with the room compliance rate for all developments but the "Exterior circulation" ones. In the latter case, the importance of urban density was offset due to higher usage of balconies, causing self-shading of the buildings, and deeming urban density less significant. Overall, full compliance with the current recommendation was only found for developments built in zones of no more than 1,9 m^3/m^2 urban density.

5.3. Policy implications

Urban densities higher than 2 m^3/m^2 were shown to negatively affect compliance of the evaluated developments. The need to satisfy the current housing demand and the non-binding formulation of the current DF_P requirement imply that there is a risk developers will not consider it, in order to provide the necessary number of apartments. The present research indicates that in a similar housing crisis, during the "record years" (1961–1974), the higher urban density and the need for larger apartments led to developments of lower daylight levels, compared to preceding developments (1940–1960).

5.4. Further research

There are several aspects of this research that were not presented in this paper, but which pertain to future investigations. The study generated an enormous amount of data regarding real apartment layouts, dimensions and geometrical characteristics, as well as detailed information on actual surroundings per development. Factoring this information with results using different daylight metrics can highlight the suitability or limitations of each metric. The difference in compliance when using different criteria (Figs. 4 and 5) indicates that the decision on the evaluation criteria deems different building types better or worse performing compared to other types. Consequently, more metrics need to be evaluated to ensure the right indicator for assessing daylight performance, if the intention is to reformulate the current requirement. Such a reformulation implies that research is conducted in terms of the occupants' perception of daylight conditions within their premises.

Declarations of interests

None.

Funding

This research was financially supported by the Swedish Energy Agency (Energimyndigheten) as part of the third cycle degree studies of the first author in Lund University, Sweden.

Acknowledgements

The authors would like to thank Marja Lundgren and Malin Alenius of White Architects and Paul Rogers of BAU for discussions and contributions during the initial building selection process. Special thanks to Max Tillberg of Bengt Dahlgren AB for his valuable remarks made in the early stages of this project's development.

References

[1] A.R. Webb, Considerations for lighting in the built environment: non-visual effects of light, Energy Build. 38 (2006) 721–727.

[2] M.A.R. Joarder, Incorporation of Therapeutic Effect of Daylight in the Architectural Design of In-Patient Rooms to Reduce Patient Length of Stay (LoS) in Hospitals, Loughborough University, 2011.

[3] M.B.C. Aries, M.P.J. Aarts, J. van Hoof, Daylight and health: a review of the evidence and consequences for the built environment, Light. Res. Technol. 47 (1) (2015) 6–27.

[4] B. Mary Jean, E.J. David, Residential Light and Risk for Depression and Falls: Results from the LARES Study of Eight European Cities, Public Health Reports, 2011, p. 131 1974-.

[5] M.-C. Dubois, N. Gentile, C.N.D. Amorim, W. Osterhaus, S. Stoffer, R. Jakobiak, D. Geisler-Moroder, B. Matusiak, F.M. Onarheim, E. Tetri, Performance evaluation of lighting and daylighting retrofits: results from IEA SHC task 50, Energy Procedia 91 (2016) 926–937.

[6] M.-C. Dubois, K. Flodberg, Daylight utilisation in perimeter office rooms at high latitudes: investigation by computer simulation, Lightning Research and Technology (1) (2013) 52.

[7] Biophilic Cities. www.biophiliccities.org. (Accessed September 10 2018).

[8] BOVERKET, National Board of Housing, Building and Planning, (2018) https://www.boverket.se/en/start/ , Accessed date: 10 September 2018.

[9] OMNI, Boverket, 700000 New Homes Must Be Built, (2016) https://omni.se/boverket-700-000-nya-bostader-maste-byggas/a/1k9B Accessed September 10.

[10] BOVERKET, Boverket's building regulations - mandatory provisions and general recommendations, BFS 2011:6 with amendments up to BFS 2018:4, (2018) pp. 1–146 https://www.boverket.se/contentassets/a9a584aa0e564c8998d079d752f6b76d/konsoliderad_bbr_2011-6.pdf.

[11] P. Tregenza, J. Mardaljevic, Daylighting buildings: standards and the needs of the designer, Light. Res. Technol. 50 (1) (2018) 63–79.

[12] W. Julian, Daylighting Standards, Codes and Policies, International Conference on Daylighting Technologies for Energy Efficiency in Building, Ottawa, Canada, 1998, pp. 265–269.

[13] M. Boubekri, F. Fran, Daylighting, Architecture and Health: Building Design Strategies, [Elektronisk resurs], Architectural Press, 2008 2008.

[14] S. Darula, J. Christoffersen, M. Malikova, Sunlight and insolation of building interiors, Energy Procedia 78 (2015) 1245–1250.

[15] Building Code FEK 59/1989, Series D, The National Printing House, Greece, 1989, pp. 525–556.

[16] S. Kunkel, E. Kontonasiou, A. Arcipowska, F. Mariottini, B. Atanasiou, Indoor Air Quality, Thermal Comfort and Daylight - Analysis of Residential Building Regulations in Eight EU Member States, (2015), p. 100.

[17] IES-LM-83-12, Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), Illuminating Engineering Society, New York, US, 2012, p. 14.

[18] CEN, European Standard - Daylight in Buildings, (2018) EN-17037.

[19] SIS, Standardiseringskommissionen I Sverige - SVENSK STANDARD SS, (1988) 91 42 01.

[20] SCB, Statistics Sweden - Dwelling Stock 31/12/2017, (2018).

[21] SCB, Statistics Sweden - Tables and Graphs, Households by Housing Type and Municipality on 31/12/2017, Excel file), 2018.

[22] SCB, Statistics Sweden - Number of Dwelling by Region, Type of Building and Period of Construction, (2018).

[23] J. Rådberg, A. Friberg, Svenska Stadstyper: Historik, Exempel, Klassificering, Stockholm: KTH högskoletr., Stockholm, 1996 1996.

[24] T. Hall, M. Rörby, Stockholm: the Making of a Metropolis, Routledge, Taylor & Francis Group, London & New York, 2009.
[25] T. Hall, S. Vidén, The Million Homes Programme: a review of the great Swedish planning project, Plann. Perspect. 20 (3) (2005) 301–328.
[26] Svensk Författningssamling, Stadsplanelag SFS 142 (1931) 1931.
[27] C. Chatzipoulka, R. Compagnon, M. Nikolopoulou, Urban geometry and solar availability on façades and ground of real urban forms: using London as a case study, Sol. Energy 138 (2016) 53–66.
[28] Stockholm Stad, Dataportalen, 3D-Building Blocks, (2018) http://dataportalen.stockholm.se/dataportalen/GetMetaDataById?id = e57466f1-85ac-4a1a-89eb-f82df609c59a.
[29] ESRI, ArcGIS ArcMap, (2016).
[30] V.5 Rhinoceros, Robet Mcneel and Associates, (2018).
[31] Grasshopper, Algorithmic Modelling for Rhino, Robet Mcneel and associates, 2018.
[32] B. Grünbaum, Convex Polytopes vol. 2, Springer, cop, New York, 2003 2003.
[33] T.A.L. Martins, L. Adolphe, L.E.G. Bastos, From solar constraints to urban design opportunities: optimization of built form typologies in a Brazilian tropical city, Energy Build. 76 (2014) 43–56.
[34] Stockholm Stad, Bygg Och Plantjänsten, (2018) http://insynsbk.stockholm.se/Byggochplantjansten/Startsida-ny/.
[35] Lantmäteriet, Swedish Surveying and Cadastral Agency, (2018).
[36] G. Ward-Larson, R. Shakespeare, Rendering with Radiance: the Art and Science of Lighting Visualization, Morgan Kaufmann Publishers Inc, 1998.
[37] M. Sadeghipour Roudsari, M. Pak, Ladybug: a parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design, Proceedings of the 13th International IBPSA Conference Held in Lyon, France, 2013, pp. 3128–3135.
[38] D. Jarvis, M. Donn, Comparison of Computer and Model Simulations of a Daylit Interior with Reality, International Building Persformance Simulation Association, IBPSA)/Building Simulation, Prague, Czech Republic, 1997 1997.
[39] M. Aizlewood, P. Laforgue, R. Mittanchey, W. Carroll, R. Hitchcock, Data sets for the validation of daylighting computer programs, Proceedings of the Daylighting'98 Conference, International Conference on Daylighting Technologies and Energy Efficiency in Buildings, 1998, pp. 11–13.
[40] M.S. Ubbelohde, C. Humann, Comparative evaluation of four daylighting software programs, Proceedings of ACEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, 1998, pp. 23–28.
[41] J. Mardaljevic, Validation of a lighting simulation program under real sky conditions, Light. Res. Technol. 27 (4) (1995) 181.
[42] J. Mardaljevic, Daylight Simulation: Validation, Sky Models and Daylight Coefficients, Doctoral Dissertation, De Montfort University, 1999.
[43] J. Mardaljevic, J. Christoffersen, 'Climate connectivity' in the daylight factor basis of building standards, Build. Environ. 113 (2017) 200–209.
[44] E.S. SS-EN-12464-1, Light and Lighting - Lighting of Work Places - Part 1: Indoor Work Places, Swedish Standards Institute (SIS), Stockholm, 2011.
[45] C. Reinhart, Daylight performance predictions, in: J. Hensen, R. Lamberts (Eds.), Building Performance Simulation for Design and Operation, Spon Press, London; New York, 2011, pp. 235–276.
[46] Grow Smarter: transforming cities for a smart, sustainable Europe. http://www.grow-smarter.eu/home/. (Accessed September 21 2018).
[47] M.-C. Dubois, Impact of Shading Devices on Daylight Quality in Offices: Simulations with Radiance, Univ., Lund, 2001 2001.
[48] D. Movilla Vega, D. Hallemar, 99 Years of the Housing Question in Sweden, first ed., Studentlitteratur, Lund, 2017.
[49] C.F. Reinhart, V.R.M. LoVerso, A rules of thumb-based design sequence for diffuse daylight, Light. Res. Technol. 42 (1) (2010) 7–31.
[50] D.H.W. Li, S.L. Wong, C.L. Tsang, G.H.W. Cheung, A study of the daylighting performance and energy use in heavily obstructed residential buildings via computer simulation techniques, Energy Build. 38 (11) (2006) 1343–1348.
[51] R. Compagnon, Solar and daylight availability in the urban fabric, Energy Build. 36 (2004) 321–328.
[52] E. Saratsis, T. Dogan, C.F. Reinhart, Simulation-based daylighting analysis procedure for developing urban zoning rules, Build. Res. Inf. 45 (5) (2017) 478–491.
[53] P.A. Sattrup, J. Stromann-Andersen, Building typologies in northern European cities, J. Architect. Plann. Res. 30 (1) (2013) 56–76.
[54] J. Mardaljevic, L. Heschong, E. Lee, Daylight metrics and energy savings, Light. Res. Technol. 41 (3) (2009) 261–283.

Paper 3

Building and Environment 185 (2020) 107276

Contents lists available at ScienceDirect

Building and Environment

journal homepage: http://www.elsevier.com/locate/buildenv

Daylight compliance of residential spaces: Comparison of different performance criteria and association with room geometry and urban density

I. Bournas

Energy and Building Design, Department of Architecture and Built Environment, Box 118, SE-22100, Lund, Sweden

A R T I C L E I N F O

Keywords:
Daylight
Compliance
Residential
Geometry
Urban density

A B S T R A C T

Currently, policy makers in Sweden are considering updating building regulations with respect to daylight provision. Given this context, the present paper aims to provide insight on the level of compliance of residential spaces when tested against five daylight performance criteria. These included the criterion currently in force in Sweden, the two performance criteria set by European Standard EN17037, a daylight factor-based criterion (BREEAM) and a climate-based criterion founded on the UDI metric. Compliance was tested by performing Radiance simulations on a representative sample of Swedish multi-dwelling buildings, including 10888 rooms. The criteria were compared according to the compliance they yield for different buildings and room types. Compliance per criterion was also associated with room geometry to evaluate which geometric measures affect it most substantially, and with urban density to evaluate which criterion best captures the effect of surrounding obstructions. Results indicate that the implementation of different criteria deem different building types to be better or worse performing. A consistent finding is that the vast majority of evaluated spaces are deemed to be incompliant when tested against the daylight-factor-based criterion of EN17037, which is significantly harder to comply with compared to its climate-based counterpart. The highest compliance is achieved when testing against the current Swedish criterion. The results also indicate that the Vertical Sky Component and glass-to-floor ratio affect compliance most substantially compared to other geometric measures. Finally, when daylight compliance was associated with urban density, the strongest association was acquired when rooms were tested using the UDI criterion.

1. Introduction

Sweden's steady population growth during the past years [1] has partly dictated the building development process, leading to the expansion or densification of urban areas in order to provide cities with the necessary amount of residential building stock. In an effort to facilitate this process, the government initiated a comprehensive review of building regulations in 2017, with the aim to re-formulate certain sections to align with European standards, as well as to allow for increased construction [2]. At the same time, concern was raised regarding the impact of ongoing densification on daylight availability for residences [3,4]. Policy makers are thus faced today with the need to facilitate construction work all the while not compromising adequate daylight levels for new constructions. To do so, they are in need of suitable daylight performance criteria.

The current daylight criterion stipulated by building code BFS 2011:6 [5] has been criticized by academia and practitioners as in need of modernization [4,6,7], due to its simplistic formulation that dates effectively from 1975 [8]. This concern was productive in highlighting the criterion shortcomings, and raised the awareness about possible improvements to its framework, which is currently based on a single point Daylight Factor [9]. Developers on the other hand have expressed their issues with daylight regulations, voicing the need for amendments that will allow them to build cost-efficiently, for instance, to maximize the amount of apartments in a given plot or to maximize the depth of an apartment in a given building plan. As Tregenza and Wilson put it: *daylighting requirements are effectively constraints on the form and size of buildings and therefore limits on the profitability of an investment* [10]. The financial pressure on policy may be the reason why the Building Rules Modernisation Committee [11] proposed recently the exclusion of the cooking space, i.e. the kitchen, from daylight evaluations [12]. The financial pressure by developers can be considered productive, as it aims

---

E-mail address: iason.bournas@ebd.lth.se.

https://doi.org/10.1016/j.buildenv.2020.107276
Received 29 June 2020; Received in revised form 23 August 2020; Accepted 6 September 2020

to satisfy the housing demand, but it is not based on scientific evidence pertaining to occupant needs or preferences. In fact, occupants have reported in two independent studies in Sweden that the kitchen is the room they clearly prioritize in terms of daylight admittance [3,6].

In practice, a standard level of daylight availability depends both on technical requirements and economic feasibility [13]. It should translate to (at least) a minimum illumination level, and at the same time not hinder the construction process with infeasible targets. Different criteria may be "easier" or "harder" to comply with, depending on illuminance thresholds or extents of analysis areas embedded in their formulations. A criterion that is very hard to meet runs the risk of being deprecated by practitioners, especially if it is not a mandatory one. A criterion that is very easy to comply with most probably does not ensure adequate illuminance levels. Effectively, different criteria may yield different results in terms of compliance. These differences are evaluated in this study, considering five criteria that are formulated using various illuminance thresholds, analysis areas and time bases for evaluations.

1.1. *Objective*

The present paper aims to provide insight on the level of compliance of residential spaces when tested against different daylight criteria that exist today. A goal of this study is to highlight criteria differences, i.e. which criteria yield higher or lower compliance, and for what building or room type. Similarities or differences between criteria are evaluated on the basis of compliance rates (percentage of compliant rooms). In addition, the effect of room geometry is evaluated, to identify which attributes play the most significant role for compliance. Compliance is also associated with urban density, to evaluate which criterion yields results that best reflect the effect of surrounding obstructions. Eventually, the study aims to provide policy makers with information that may prove useful for devising (or not devising) specific daylight requirements, both in Sweden and internationally. To achieve this, the analysis incorporates a variety of performance indicators that are both daylight-factor-based and climate-based, and deploys them in a large sample (n = 10888) that is representative of residential spaces.

2. Methodology

The study involved four main stages: i) Selecting the building sample, ii) Modelling and simulating daylight scenes, iii) Selecting performance criteria and iv) Processing data. Each stage is described in the following sections.

2.1. *Sample selection*

A sample of multi-dwelling buildings was selected within the metropolitan region of Stockholm (Lat.: 59.93 °N) and the nearby city of Örebro (Lat.: 59.72 °N). According to the latest building stock data, 51% of existing dwellings are housed in multi-dwelling buildings [14]. This type of dwelling is the dominant housing type in the largest Swedish municipalities, and the most commonly used in construction every year since 1985 [15]. The buildings were selected according to construction year and architectural typology. With respect to construction year, the number of selected apartments was proportional to the actual construction rate that occurred per decade, in the timespan between 1920 until 2000. With respect to architectural typology, buildings were selected based on their relevance to major architectural block typologies adopted in Swedish urban planning history, as categorized by Hall and Rörby [16] and Rådberg and Friberg [17].

The sample included eight typologies identified in 25 residential developments, as shown in Fig. 1 (codes A – Y). At least three

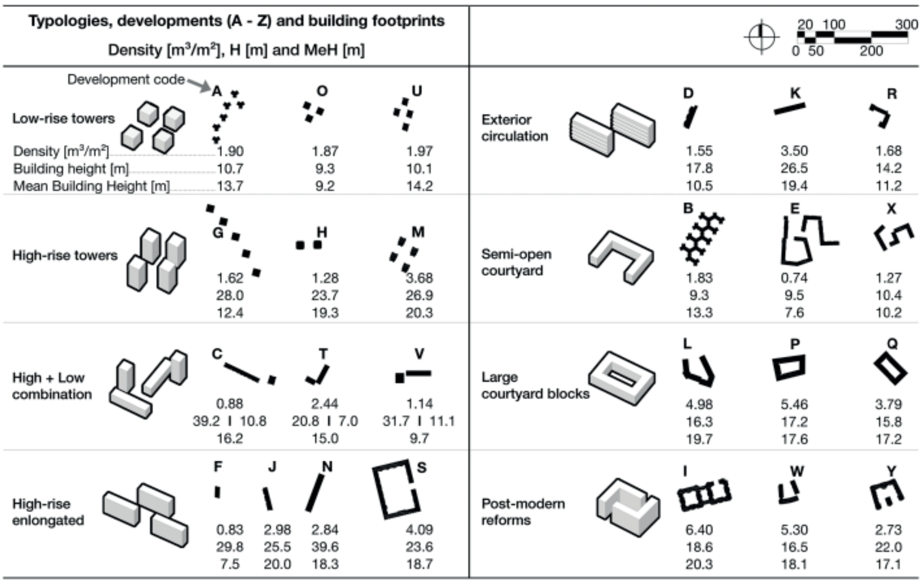


Fig. 1. Selected building sample. The eight architectural typologies, the 25 developments (A–Z) with their building footprints, and Density, Building Height and Mean Building Height indicators.

developments per typology were selected. The developments comprised 54 buildings, which included 3151 apartments with 10888 individual rooms. The building footprints are shown below the corresponding development codes. Depending on typology, developments consisted of one or more buildings e.g. development *A* (*low-rise towers* typology) consists of six buildings. Three relevant urban indicators are shown below the building footprints. The urban density (Density, [m^3/m^2]) is the quotient of the built volumes in a 250 m radius divided by the total urban area of the region that encloses these volumes. The height (H, [m]) is the maximum height of the evaluated development measured from street level. The mean building height (MeH, [m]) is the average height of surrounding buildings in the 250 m radius, weighted by footprint area.

2.2. Modelling, analysis areas and simulation settings

Modelling included i) surrounding obstructions and ii) the evaluated buildings. Fig. 2 shows an example (development *X* of *Semi-open courtyard* typology); the same process was followed for all developments. On the top left of Fig. 2a, the blue line is the convex hull [18] of the footprint outline endpoints, i.e. the smallest convex area that includes all buildings belonging to the development. The considered surroundings only included buildings located within a 250 m offset of the convex hull (dark grey footprints). The footprints and heights of surroundings were retrieved in vector format from [19] and were imported from ArcGIS ArcMap [20] to Rhinoceros 3D [21]. The data were further processed in Grasshopper [22] to cull surroundings within the 250 m radius. Fig. 2b shows the considered rooms in blue hue. The rooms were modelled according to documentation drawings retrieved from Stockholm City Planning Office [23]. Following the Swedish building code, the study only included rooms "*where people are present other than occasionally*" [24], namely bedrooms (n = 3792), living rooms (n = 2879), kitchens (n = 3025) and dining rooms (n = 1192). Surfaces were designed with a 0.05 m tolerance, except for window frames, which were designed with a 0.03 m tolerance, according to drawings and good practice recommendations [25].

Three analysis areas were used to calculate the daylight metrics embedded in the considered criteria. The first analysis area was a 0.3 m × 0.3 m point-grid, elevated 0.8 m above floor level, excluding a 0.5 m band from walls, shown with white points in Fig. 2c. The second area was the same 0.3 m × 0.3 m point-grid, but extending across the total room area (additional points are shown in black for the bottom-right room in Fig. 2c). Depending on criterion, metrics were calculated over different portions of these areas, as described further down in section *2.3 Compliance criteria*. A third analysis area was set to calculate the Swedish criterion. DF_P was calculated on the red points shown in Fig. 2c, which according to definition are "*located halfway through the room depth, 1 m from the darkest lateral wall, and 0.8 m above floor level*" [9]. Since the "*darkest lateral wall*" was unknown prior to simulation, the DF_P was calculated in all possible point locations as per the definition, which is why there are two red points in each room in Fig. 2c. During post-processing, the lowest value between these points was considered as the DF_P value.

Simulations were performed using Radiance [26] through the interfaces provided by Grasshopper plugins Honeybee (legacy) and Honeybee (plus) [27]. Radiance is a backward raytracer that has been extensively validated for agreement with illuminance measurements in full-scale spaces [28,29]. Honeybee (legacy) was used to calculate point-in-time metrics, i.e. daylight factors, while Honeybee (plus) was used for metrics derived from annual simulations. The reason for this differentiation is that Honeybee (plus) offers a more accurate calculation model for annual simulations, as it utilizes different Radiance executables that treat direct solar contributions with a higher spatial accuracy compared to Honeybee (legacy) [30], which uses the standard daylight coefficient method [31]. Different executables are the reason for the different Radiance rendering settings per simulation type (point-in-time or annual) in Table 1A. The surface optical properties used are shown in Table 1B, and included standard values [32,33]. All opaque surfaces were modelled as Lambertian diffusers, which is a realistic assumption for typical building interiors. More details on geometric considerations may be found in [4].

2.3. Compliance criteria

Each room was tested against five criteria. These criteria are formulated using different metrics, with different illuminance threshold values, analysis areas and time bases, summarized in Table 2. Following is a short description of each criterion:

2.3.1. The point daylight factor compliance criterion (SS914201)

This is the criterion in the current Swedish building code [5]. The code refers to Swedish Standard SS914201 [9] for the calculation method of a point Daylight Factor (DF_P). DF_P should be calculated for a point *located halfway through the room depth, 1 m from the darkest lateral wall, 0.8 m above floor level*. A room is considered compliant if $DF_P \geq 1\%$. DF_P is calculated under a CIE Overcast Sky [34]. It should be noted here

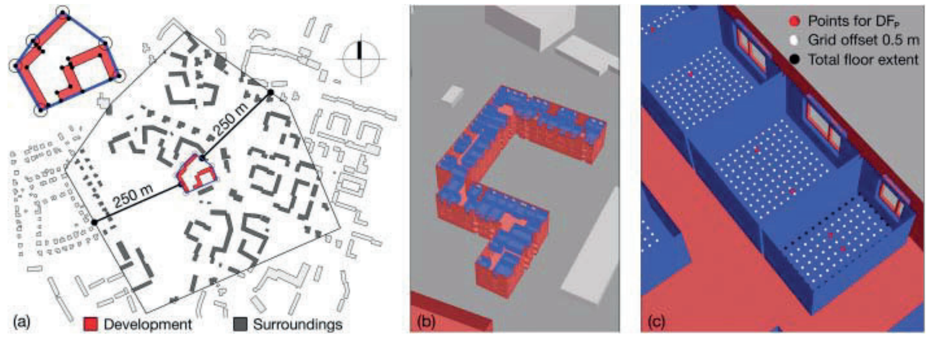


Fig. 2. a) Considered surroundings, b) Perspective of development *X* and c) The DF_P points (red points), the 0.3 x 0.3 grid points that exclude the 0.5 m band from walls (white points), and the additional points included in the 0.5 m band (black points). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
A) Radiance rendering settings and B) Surface optical properties.

A. Raytracing settings

Rendering setting	point-in-time	annual
ambient bounces (ab)	7	7
ambient divisions (ad)	2048	25000
ambient supersamples (as)	512	4096
ambient accuracy (aa)	0.1	0
ambient resolution (ar)	variable	0
ambient value (av)	0	0
direct threshold (dt)	0.03	0.02
direct certainty (dc)	1	1
direct subsampling (ds)	0.05	0.05
direct jittering (dj)	1	1
limit weight (lw)	$1 \cdot 10^{-4}$	$4 \cdot 10^{-7}$
limit reflection (lr)	7	7

B. Optical properties

Surface type	**Reflectance**	**Transmittance**
Walls (interior), closets	70%	–
Ceiling	80%	–
Floor	30%	–
Window glass	–	70%
Window frame	80%	–
Window head, jamb and sill	50%	–
Balcony ceiling	70%	–
Balcony floor	30%	–
Ground	20%	–
Surrounding facades	30%	–
Surrounding roofs	30%	–
Water	50%	–
Railing	–	variable

that a considerable portion of the evaluated rooms (85%) were not specifically designed to comply with this criterion, as the criterion effectively came into force in 1975, while the sample included multiple buildings constructed earlier than that, as far as in 1926 [4].

2.3.2. *The useful daylight illuminance compliance criterion (UDI)*

This criterion was formulated specifically for this study, in order to highlight its similarity to criterion *i* in terms of compliance, all while being a climate-based criterion. According to Mardaljevic and Nabil, the UDI metric represents the annual occurrence of illuminances across a plane that fall within a "useful" range for occupants [35]. The rationale is that low illuminance levels will trigger electric lighting use, while extremely high illuminances may hinder particular tasks and trigger the use of shading, thus deeming illuminance to be "useful" only within a certain range of lux. The range has so far been defined for office spaces, and lies between 100 lx and 3000 lx [36]. This range corresponds to the scheme referred to as *UDI combined*. It accounts for the combined illuminance ranges of 100–300 lx, i.e. *UDI supplementary* (or UDI-s), and 300–3000 lx, i.e. *UDI autonomous* (or UDI-a). It is arguable that the upper UDI threshold for residential spaces could be higher than that for offices, e.g. 4000 or 5000 lx, given the different nature of the space and the performed tasks. However in the present study, a similar appreciation of daylight between offices and dwellings was assumed, thus a UDI range between 100 lx and 3000 lx was used. Due to inconsistent occupancy patterns in dwellings, the time basis for this criterion was not set to a fixed occupancy schedule (e.g. from 9:00 to 17:00), but was set to 70% of the daylight hours of the year (3066 h). The criterion was that a room should achieve a $UDI_{100\text{-}3000} \geq 70\%$ across half of the room area (excluding the 0.5 m band from walls).

2.3.3. *The BREEAM-SE good practice daylight factor compliance criterion (BREEAM)*

The BREEAM certification scheme proposes two methods to assess daylight compliance, one based on daylight factors and one based on absolute illuminance levels throughout the year [37]. The daylight factor method was deployed for this study, as the current technical manual for new construction BREEAM-SE 2017 [37] states that this method is "*intended for use in countries like Sweden*". The minimum requirements for residential spaces include average daylight factors calculated across 80% of the total room area. These daylight factors should be no less than 2.1% for kitchens and 1.6% for the rest of the rooms. Since the BREEAM technical manual provides no indication as to where the 80% of the total area should be, the present study considered the 80% that included the highest daylight factor values, resulting in the most optimistic compliance test. In addition, the criterion stipulates a minimum uniformity ratio $U \geq 0.3$, calculated excluding the 0.5 m band from walls.

2.3.4. *The European Standard compliance criterion as per the daylight factor method (EN17037-DF)*

To comply with this criterion, two daylight factor values should be achieved for Stockholm: $D_{300} \geq 2.5\%$ across 50% of the area, and $D_{100} \geq 0.8\%$ across 95% of the area, excluding the 0.5 band from walls [32]. Thresholds 2.5% and 0.8% are the required daylight factor values to achieve indoor illuminance levels of 300 lx and 100 lx respectively, under a sky with a diffuse horizontal illuminance (DHI) of 12100 lux. The latter is the median DHI in Stockholm, according to the corresponding climate file available from the EnergyPlus website [38]. The median DHI is used in the formulation of the criterion to ensure that illuminance values are provided for at least half of the daylight hours in the year. This criterion is thus based on the provision of 300 lx across 50% of the room area, and 100 lx across 95% of the room area, for at least half of the daylight hours in the year (2190 h), but is formulated using daylight factors that are somewhat location-aware, since they are

Table 2
Summary of criteria, including threshold values, time bases, areas to comply and considerations (orientation, sunlight).

	Threshold value:		Time basis	Area to comply [%]	Accounted for:	
	DF [%]	Illuminance [lx]			Orientation	Sunlight
i.SS914201	≥ 1		point-in-time	single point	No	No
ii.UDI		100–3000	70% of daylight hours	50 (excl. 0.5 m band)	Yes	Yes
iii.BREEAM	≥ 2.1[a], ≥ 1.6[b] & $U \geq 0.3$		point-in-time	80 (of total room area) 100 (excl. 0.5 m band)	No	No
iv.EN17037-DF	≥ 2.5 ≥ 0.8		point-in-time	50 (excl. 0.5 m band) 95 (excl. 0.5 m band)	No	No
v.EN17037-IL		≥ 300 ≥ 100	50% of daylight hours	50 (excl. 0.5 m band) 95 (excl. 0.5 m band)	Yes	Yes

[a] Applicable for kitchen rooms. Threshold value for average daylight factor.

[b] Applicable for the rest of the rooms.Threshold value for average daylight factor.

a function of DHI. Despite the climate-connected rationale of this criterion [39], it is still limited to the daylight factor approach, where sunlight and façade orientation are not considered, as D_{300} and D_{100} are calculated under a CIE Overcast Sky.

2.3.5. The European Standard compliance criterion as per the illuminance method (EN17037-IL)

This criterion is included in EN17037 as an alternative to criterion *iv*. It is also based on the provision of 300 lx across 50% of the room area, and 100 lx across 95% of the room area, for at least half of the daylight hours in the year (2190 h) [32]. However, this criterion requires that a detailed calculation be conducted, where hourly (or sub-hourly) internal illuminance values are computed using typical climate data. In this case, both skylight and sunlight are taken into consideration, thus climate and façade orientation are accounted for, unlike in criterion *iv*. In essence, this is the climate-based equivalent of criterion *iv*. It should be noted here that both EN17037 criteria (*iv* and *v*) are meant to be recommendations for daylight conditions, not normative. They were included in this study to demonstrate what would be the result if they came into force as mandatory criteria.

Fig. 3 illustrates differences between criteria that the reader should bear in mind. For each criterion, the percentage of compliant area (white area) is shown for two rooms that are identical in all aspects apart from orientation. For SS914201 (criterion *i*), the white area is shown indicatively, since the criterion is based on the calculation of a single point (DF_P point). Compliant and incompliant rooms are marked with "✓" and "X" respectively. Firstly, criteria *i*, *iii* and *iv* are assessed under CIE Overcast Sky conditions, while criteria *ii* and *v* are assessed under sky luminance distributions that vary throughout the year. Consequently, façade orientation is only considered by *ii* and *v*, which can be inferred from the compliant areas (equal percentages for Northeast and Southwest rooms for criteria *i*, *iii* and *iv*, unequal for criteria *ii* and *v*). Secondly, criterion *i* stipulates that a single point should achieve a daylight factor of at least 1%. This point daylight factor has previously been shown to correlate very strongly with the median daylight factor across the room area [4], which indicates that complying with criterion *i* is equivalent to achieving a daylight factor of 1% over 50% of the room area. This is significantly easier to comply with compared to criterion *iv*, which requires 2.5% over the same area. The difference is evident in Fig. 3 (SS914201: 92%, EN17037-DF: 32%). Thirdly, unlike other criteria, criterion *iii* stipulates thresholds for average daylight factors. This difference is subtle, but has a very strong effect on compliance testing. For instance, although the 1.6% DF bedroom threshold is not exceeded across 80% of the room area in Fig. 3 (BREEAM white area = 50%), the average daylight factor of 80% of the area (black outline) exceeds 1.6% by a high margin (= 3.25%), deeming the room to be compliant. Using an average value implies that high values close to the window will affect compliance disproportionally to the extent of the daylit area. The effect is amplified for BREEAM as it considers the total room area. Fourthly, criteria *ii* and *v* are both climate-based but consider different illuminance ranges. Criterion *v* does not accept low illuminances (<300 lx), while criterion *ii* does, but excludes high illuminances (>3000 lx). Therefore, the compliant area for criterion *v* lies in the region closest to the window, while for criterion *ii* it may lie deeper in the room, due to high illumination near the window (>3000 lx), as shown in Fig. 3 (Southwest: UDI incompliant area close to window). Lastly, although criteria *iv* and *v* are included in the same standard (EN17037) as two calculation methods to choose from freely, judging by the compliant areas in Fig. 3 it is evident that criterion *v* yields higher compliance for the displayed room. The fact that criterion *v* accounts for sunlight is why it can yield a larger compliant area, in any orientation.

2.4. Data analysis

2.4.1. Compliance rates

The study calculated the compliant rate, i.e. the percentage of compliant rooms according to each criterion. Compliance rates were calculated per building typology, development and room function. The significance of the difference between two given compliance rates (e.g. two rates yielded by different criteria) was evaluated with Chi-Square tests of independence [40]. Since the sample sizes in this study were large, all differences were found statistically significant ($p < 0.05$). It was therefore more meaningful to assess the magnitude of the differences, i.e. detect the most substantial differences by calculating effect sizes. Cohen's effect size h [41] was used for this purpose. Cohen suggests that h values of 0.2, 0.5 and 0.8 represent *small*, *medium* and *large* effects respectively. Considering this, compliance rate differences with h values higher than 0.5 were considered substantial.

2.4.2. Association of compliant rates between criteria

The criteria were compared pairwise at development level ($n = 25$), to assess the degree of association between the compliance rates they yield. A one-sample Kolmogorov-Smirnov test [42] revealed that compliance rates yielded by all criteria were normally distributed across developments, which led to the use of ordinary least squares to assess association. For each pair of criteria, the coefficient of determination R^2 was computed. Effectively, R^2 indicates the proportion of variance in compliance as per one criterion that can be predicted when knowing the

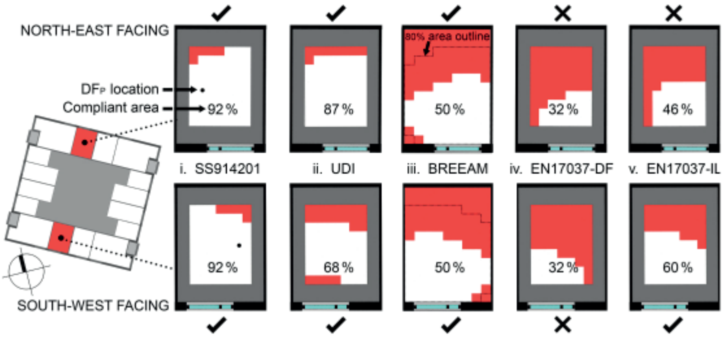


Fig. 3. Indicative differences between criteria: percentage of compliant area (white area) for a Northeast-facing and a Southwest-facing room. Compliant and incompliant rooms are marked with "✓" and "X" respectively.

compliance as per another criterion, i.e. a higher R^2 indicates a higher association between two criteria in terms of compliance.

2.4.3. Association of compliant rates with urban density

The compliance yielded at development level was also related to the degree of surrounding obstructions. This was assessed by calculating the Spearman Rank Correlation coefficient (r_S) for the association between compliance rates [%] and urban density [m^3/m^2]. The reason for using a non-parametric test in this case was that the distribution of urban density across developments was significantly non-normal, as per a one-sample Kolmogorov-Smirnov test ($D(25) = 0.189$, $p = 0.021$). The association strength was interpreted according to the three-tier effect size categorization suggested by Cohen [41], where the effect size is considered small for an absolute value of r_S lower than 0.3, medium for an absolute value between 0.3 and 0.5, and large for an absolute greater than 0.5.

2.4.4. Criteria agreement

Although two criteria could yield similar compliant rates, the rates could be a result of different rooms complying with each criterion, i.e. the rooms that complied with one criterion may not necessarily be the same rooms that complied with the other criterion. For this reason, the criteria were compared pairwise, assessing the number of rooms that had i) identical compliance (rooms either compliant with both criteria or compliant with none of the two criteria), ii) compliance only with the first criterion and iii) compliance only with the second criterion. From these room numbers, the probability of one criterion agreeing with another criterion was assessed (rooms with identical compliance divided by the total number of rooms). Similarly, the probability that a criterion *x* is complied with when a criterion *y* is not was compared to the probability that criterion *y* was complied with when criterion *x* was not, to assess criteria disagreement and which criterion is harder to comply with.

2.4.5. Effect of room geometry

The effect of geometry on compliance was evaluated to assess which design attributes have a substantial impact. Attributes included i) room floor area (A_{FLOOR}), ii) room depth (D), iii) room width (W), iv) glazing area (A_G), v) glass-to-floor ratio (GFR), vi) glass-to-wall ratio (GWR) and vii) glass-to-internal walls ratio ($GW_{INT}R$), which is the glazing area relative to the sum of interior wall areas. In addition, the effect of the Vertical Sky Component (VSC, [43]) was assessed, to evaluate the effect of surrounding obstructions. The VSC was calculated according to Littlefair [44], and the exact method followed is described in [45]. To assess the effect of attributes on compliance, two groups of rooms were compared per criterion: one group comprising compliant rooms, and one room comprising incompliant rooms. Every geometric attribute was compared between the two groups using Mann-Whitney U-tests. The Mann-Whitney U statistic estimates the probability that a random score from one sample (e.g. a random GFR value among compliant rooms) exceeds a random score in a second sample (e.g. exceeds a random GFR value among incompliant rooms) [46]. The test was appropriate here as i) geometry data were not normally distributed, ii) the compared groups were independent, and iii) there were outliers for certain attributes. In this study, a trivially small effect but nonetheless significant due to the large sample size could lead to overvaluing the importance of an attribute [47]. Indeed test results were statistically significant ($p < 0.001$) for the vast majority of geometric attributes. Therefore, effect sizes were considered instead of significance. For Mann-Whitney U-tests, the appropriate effect size is Cohen's *r* [48]. Cohen suggests that the effect size is small when *r* is 0.1, medium when *r* is 0.3, and large when *r* is 0.5 [41]. A geometric attribute was considered to affect compliance substantially when its effect size was higher than 0.3.

3. Results and discussion

3.1. Compliance per typology

The compliance rate per criterion is shown in Table 3, for each typology and for all 10888 rooms (Overall compliance). Typology ranking according to compliance is shown in italics, for instance, the *semi-open courtyard* typology ranks first according to SS914201 (rank *1*), and fourth according to EN17307-IL (rank *4*). SS914201 yields the highest compliance rates, which range from 40% to 95% across different typologies, and yields an overall compliance equal to 69%. The EN17037-DF criterion yields the lowest compliance rates (Overall compliance = 16%). Chi-Square tests indicated that EN17037-DF compliance is significantly lower compared to all other criteria ($p < 0.001$). In particular, it was substantially lower compared to SS914201, UDI and BREEAM (*h*: 1.12, 0.96 and 0.89 respectively), and moderately lower compared to EN17037-IL (*h*: 0.64).

Certain patterns can be observed with respect to typologies. *High-rise towers* rank consistently first or second (ranks *1* or *2*). The bottom three ranks (*6 – 8*) correspond for most criteria to *exterior circulation, post-modern reforms* and *large courtyard* typologies. Typologies *post-modern reforms* and *large courtyard* are located in areas of high urban density (Fig. 1, Density), and comprise buildings that are lower than their surroundings (Fig. 1: Building Height <Mean Building Height). The worst performing typology is *exterior circulation*, which is ranked at the bottom by daylight-factor-based criteria and sixth by climate-based criteria, although its developments are not located in highly dense urban areas (Fig. 1, Density for *D, K, R*). Buildings belonging to this typology have the highest percentage of rooms with a balcony (55%–68% of rooms, depending on building). In essence, the balcony blocks the view to the higher parts of the sky dome, which are the most luminous parts in the CIE Overcast Sky model [34]. The three aforementioned typologies do not populate the bottom three ranks in one case: the BREEAM criterion. This criterion ranks *post-modern reforms* fifth (rank *5*), and interestingly, it yields the highest compliance rate for this typology (49%) among all criteria, making it the only typology for which SS914201 does not yield the highest compliance. The reason for this is that the BREEAM criterion is formulated to favour specific room designs found in this typology; this is elaborated further down in section 3.5. Finally, Table 3 indicates that SS914201 and UDI rank typologies similarly, although SS914201 compliance rates are consistently higher.

3.2. Compliance per development

Fig. 4 shows compliance rates at the development level (A – Y). The geometric attributes of rooms are more homogenous within a development than within a typology. The absolute difference between compliance rates of SS914201 and UDI (i – ii), and EN17037-IL and EN17037-DF (v – iv) are shown below the development codes. Fig. 4 confirms the previous findings: SS914201 yields the highest compliance rates (white bars), while EN17037-DF yields the lowest (dark grey bars). Criteria SS914201 and UDI yield similar compliance rates (i - ii), with the absolute difference being less than 15% for all developments except for *large courtyard* (*L, P, Q*) and development *I*. These four developments are located in denser areas (Fig. 1, Density for *I, L, P, Q*). Further investigation revealed that rooms complying only with DF_P do so marginally ($DF_P < 1.5\%$ in 98% of rooms, $DF_P < 1.25\%$ in 68% of rooms). Differences between the two EN17037 criteria (v – iv) are profound for most developments, and are below 20% only when compliance rates are low, i.e. in developments *D, I, P, Q, T*. However, the relative difference ((v – iv)/v · 100%) for *D, I, P, Q, T* is high (100%, 97%, 79%, 94% and 40% respectively). Developments *I* and *Y* comply more so with BREEAM than with the rest of criteria, due to room geometric characteristics "favoured" by BREEAM, which are examined in section 3.5. Similarly to Table 3, *large-courtyard, post-modern reforms* and *exterior circulation* developments are shown to underperform.

Table 3
Compliance rates and ranking of typologies per criterion.

Typology	n	Compliance rate (%) and ranking (*1 - 8*) per performance criterion									
		SS914201		UDI		BREEAM		EN17037-DF		EN17037-IL	
semi-open courtyard	1304	*1*	95	*1*	88	*1*	*91*	*4*	10	*4*	*51*
high-rise towers	1908	*2*	86	*2*	79	*2*	*80*	*1*	40	*1*	*72*
low-rise towers	530	*3*	82	*3*	79	*4*	*68*	*5*	7	*2*	*61*
high + low combination	864	*4*	81	*4*	79	*3*	*73*	*3*	14	*3*	*53*
high-rise enlongated	2671	*5*	64	*5*	61	*7*	*35*	*2*	23	*5*	*48*
large courtyard	1535	*6*	52	*8*	32	*6*	*46*	*7*	2	*8*	*16*
post-modern reforms	1458	*7*	47	*7*	35	*5*	*49*	*6*	5	*7*	*19*
exterior circulation	618	*8*	40	*6*	39	*8*	*27*	*8*	0	*6*	*27*
Overall compliance	10888		69		61		57		16		45

3.3. Compliance per room function

Fig. 5 shows compliance rates per room function (K: kitchen, L: living room, B: bedroom and D: dining room) including all 10888 rooms, and the compliance difference between SS914201 and UDI (i – ii) and between EN17037-IL and EN17037-DF (iv – v). It is shown that kitchens are the least compliant rooms, followed by living rooms and bedrooms, which have similar compliance rates. Dining rooms achieve the highest compliance, with at least 50% of the rooms complying with each criterion. Comparing criteria within room functions, SS914201 yields the highest compliance and EN17037-DF the lowest, consistently across functions. There is a difference below 10% between SS914201 and UDI for all functions, and a higher difference (22% - 37%) between the two EN17037 criteria, which indicates that the agreement between SS914201 and UDI is persistent when stratifying rooms per function, and so is the disagreement between the two EN17037 criteria.

Some criteria require that different metrics exceed specific thresholds, for a room to be compliant. The reader may refer to Table 2 for a summary of these metrics. Fig. 6 shows the distribution of each metric per room function, with metric thresholds indicated by the red line in each violin plot. Compliance rates are shown below function abbreviations K, L, B, D. Room functions rank similarly to Fig. 5, with kitchens consistently underperforming, followed by bedrooms and living rooms, while dining rooms clearly outperform all other functions. The only exception for kitchens is the uniformity U threshold of BREEAM, which is exceeded by 76% of kitchens. This rate includes rooms that are dim across the total floor area thus have by definition high daylight uniformity (uniformly dark rooms). Comparing criteria it is shown that SS914201 and BREEAM DF yield similar compliance rates, while the two EN17037 criteria differ significantly, regardless of metric. To this end, it can be observed that the low compliance rate of EN17037-DF in Table 3 (Overall compliance = 16%) is mainly due to the $DF \geq 2.5\%$ requirement, and less due to the $DF \geq 0.8\%$ requirement. Similarly, the 300 lx requirement of EN17037-IL yields lower compliance compared to the 100 lx requirement. This highlights how much more demanding the EN17037 criteria are compared to SS914201, which only requires the equivalent of 100 lx under an overcast sky ($DF_P \geq 1\%$).

3.4. Associations between criteria

In Fig. 7 criteria are compared pairwise according to compliance rate per development ($n = 25$). The five regression models shown in Fig. 7a–e are the ones with the highest R^2 among all possible pairs of criteria. Additionally, Fig. 7f was included to illustrate the high disagreement between the two EN17037 criteria. The highest association is observed between UDI and SS914201 (Fig. 7a, $R^2 = 0.927$). The good fit effectively means that the "static" SS914201 criterion could be replaced by a climate-based criterion, without high compliance differences. The second highest correlation was found between UDI and EN-17037-IL (Fig. 7b, $R^2 = 0.779$), followed by BREEAM vs SS914201 (Fig. 7c, $R^2 = 0.762$); however there are higher errors in these models compared to Fig. 7a. The rest of the models show weaker linear associations. In particular, Fig. 7f shows a high disagreement between the EN17037 criteria ($R^2 = 0.351$), which corroborates the results of all previous sections. This finding is worth noting, as the two criteria are included in the same standard, for the provision of the same illuminance thresholds, across the same room area and the same timespan throughout the year. The fact that the climate-based indicator yields higher compliance implies that a more accurate representation of sky conditions can reveal a different potential of a design to admit daylight, in particular a higher potential.

3.5. Differences between criteria

Fig. 8 shows results from a pairwise comparison of criteria on room level. Bold numerals indicate the number of rooms with identical compliance (rooms that pass both criteria or fail both criteria). Numerals in italics show the number of rooms that comply with only one of the two criteria. The left-side values indicate the number of rooms that comply only with the criterion of the first column, for instance, 1094 rooms comply with SS914201 but do not comply with UDI. The right-side values indicate the number of rooms that comply only with the criterion on the first row, for instance 259 rooms comply with UDI but do not comply with SS914201. It is shown that SS914201 and UDI yield identical compliance in 9535 out of 10888 rooms (88%), which is the highest agreement for any pair of criteria. The probability that the two criteria yield different compliance is 0.12 ((1094 + 259)/10888). The probability of a room complying only with SS914201 is 4.22 times higher than the probability of complying only with UDI ($1094/259 \approx 4.22$). The second highest agreement is between UDI and EN17037-IL (8889 rooms, i.e. agreement in 82% of rooms), which confirms that the linear fit in Fig. 7b corresponds to agreement on room level. Complying only with UDI is 14.3 times more probable than complying only with EN17037-IL. As expected, very few rooms comply only with EN17037-DF. The difference between the EN17037 criteria is extremely high. The probability of complying only with EN17037-IL is 1041 times higher than complying only with EN17037-DF.

The right part of Fig. 8 shows the number of rooms that comply with one criterion exclusively, and the number of rooms that comply with all criteria except that criterion. It is verified that EN17037-DF is the most demanding compliance criterion (2276 or 21% of rooms comply with all other criteria except EN17037-DF), while SS914201 is the least demanding. For UDI, it was found that the rooms of group A2 (complying with all criteria except UDI) had significantly higher VSC, GFR and $GW_{INT}R$ ($r = 0.54$, 0.68 and 0.54 respectively), and significantly smaller floor area, shorter depth and shorter width ($r = -0.65$, -0.78, -0.64 respectively) compared to rooms of group A1 (Mann-Whitney *U*-test, $p < 0.001$). Indicatively, Fig. 9a shows a typical room complying with all criteria except UDI. The vast majority of such rooms (92%) were small dining rooms, positioned next to the window. In essence, these dining rooms are excessively lit, which reduces UDI compliance since illuminances over 3000 lx are not accounted for. For

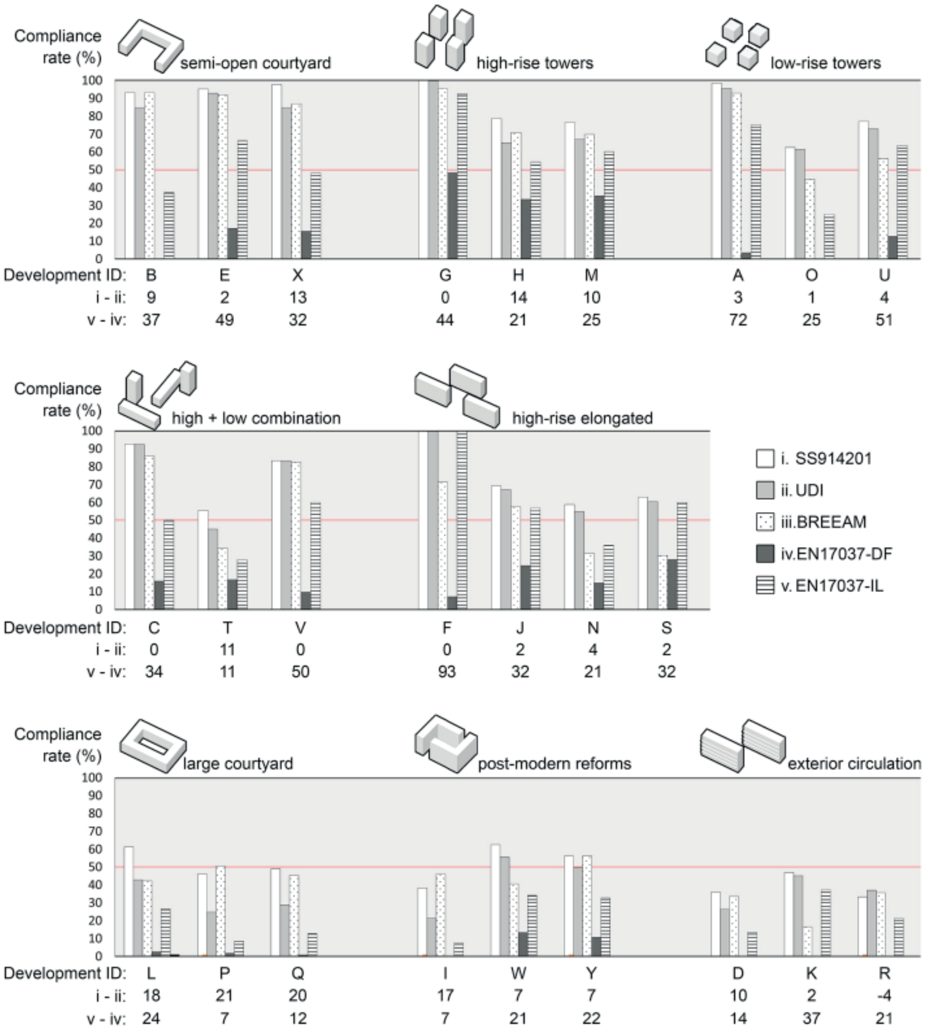


Fig. 4. Compliance rates for developments *A* – *Y* per criterion. Absolute differences between rates for SS914201 and UDI (i – ii), and between EN17037-DF and EN17037-IL (v – iv) are shown below each development code.

BREEAM, it was found that B1 rooms (complying only with BREEAM) had significantly lower VSC and GFR (r = −0.33, and −0.50 respectively), and significantly larger floor areas and longer depths (r = 0.41 and 0.44 respectively) compared to B2 rooms (complying with all criteria except BREEAM). Fig. 9b helps illustrate why these designs are “favoured” by BREEAM. In essence, they include rooms that are lit in a small region close to the window, which is not placed in the center of the facade. The BREEAM daylight factor threshold is reached, but DF_P is low as the DF_P evaluation point is located far from the window. In addition, since the area for the uniformity ratio (U) calculation does not include the 0.5 m band from walls, U is calculated based on a low average illuminance, since the room is considerably large and deep. This results in high U for the room, which is in fact a uniformly dim room, and yields compliance with BREEAM. The average daylight factor has previously

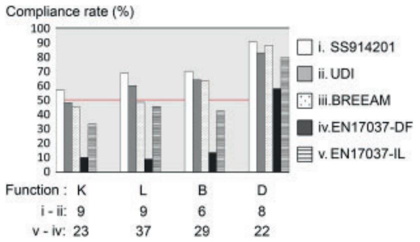


Fig. 5. Compliance rate per room function and criterion, with deviations between SS914201 and UDI (i – ii), and between EN17037-DF and EN17037-IL (v – iv).

been reported as more prone to intentional game-playing compared to other metrics [39], and the BREEAM definition of evaluation area (80% of floor area) has been criticized as being ambiguous [50].

Finally, it was tested whether the high agreement between SS914201 and UDI was due to rooms achieving illuminances between 100 and 300 lx (UDI-s) or between 300 and 3000 lx (UDI-a). The reader is referred to section 2.3.2 for a description of the UDI-s and UDI-a schemes. Fig. 10 shows the distribution of average (avg), minimum (min) and median (mdn) UDI-s and UDI-a across the room floor area, for all 10888 rooms. It is clear that UDI-a (white boxplots) lies consistently higher than UDI-s. The right-most distribution (boxplot with diagonal hatch) shows the portion of room area where UDI-a is higher than UDI-s, i.e. the portion of area where illuminances between 300 and 3000 lx occur more frequently than illuminances between 100 and 300 lx. It is shown that at least 50% of the floor area achieves higher UDI-a than UDI-s in 75% of the rooms. This can be attributed to the fact that residential rooms are arrayed in the building perimeter, and to the fact that the time base for the UDI calculation includes the best 70% of the daylight hours of the year. Observing the median measures of UDI-s and UDI-a, one can infer that complying with the UDI criterion (Table 2: 70% of the time, in 50% of the room floor area) is not possible when only one illuminance range is considered (either 100–300 lx or 300–3000 lx). This is true as the median value relates to 50% of the room area, and is shown to be below 70% for all rooms, both for UDI-s and UDI-a. This indicates that compliances shown previously for UDI were a result of combined illuminances from both ranges. The latter highlights the spatiotemporal dynamics of daylight illumination, as illuminance on room points varies significantly over time.

3.6. Association with room geometry

Table 4 shows what differentiates compliant from incompliant rooms in terms of geometry. Substantial effect sizes are marked with "*" and "**". The most influential attributes are VSC and GFR. VSC is shown to differ largely between compliant and incompliant rooms ($r \geq 0.46$) for all criteria except EN17037-DF ($r = 0.26$). GFR is influential consistently: the difference ranges from medium for BREEAM ($r = 0.34$), to large for the EN17037 criteria ($r = 0.53, 0.54$). Three geometric attributes do not differ substantially between compliant and incompliant rooms: i) room width (W) is either not different ($p > 0.05$) or marginally

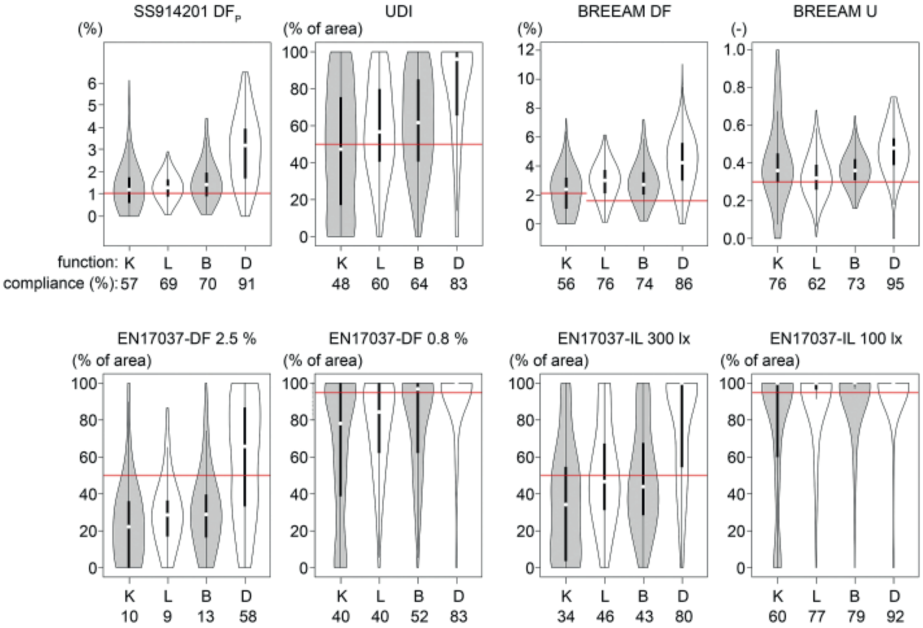


Fig. 6. Distribution of criteria metrics per room function and corresponding compliance rates. Compliance thresholds are indicated by the red line in each violin plot. Plots were created using BoxPlotR [49]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

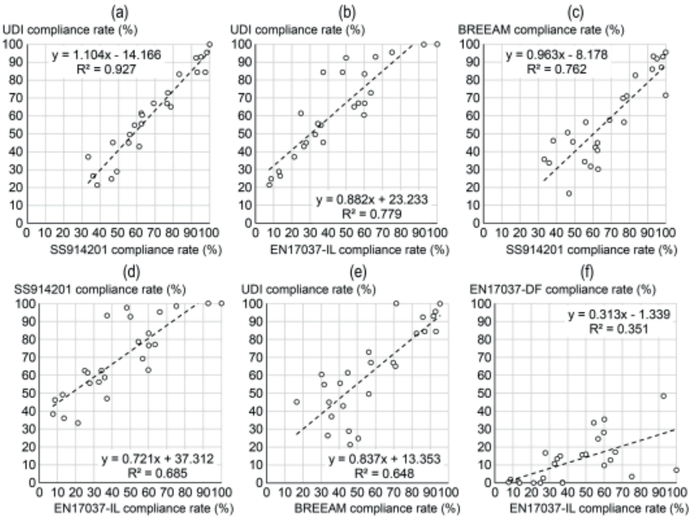
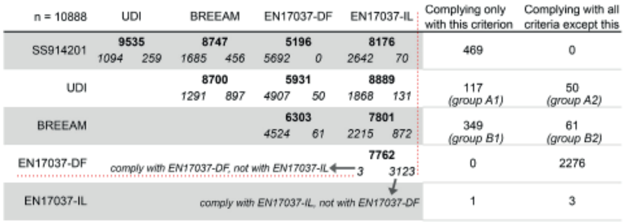


Fig. 7. Scatter plots of development ($n = 25$) compliance rates for a) UDI versus SS914201, b) UDI versus EN17037-IL, c) BREEAM versus SS914201, d) SS914201 versus EN17037-IL, e) UDI versus BREEAM, and f) EN17037-DF versus EN17037-IL.



n = 10888	UDI	BREEAM	EN17037-DF	EN17037-IL	Complying only with this criterion	Complying with all criteria except this
SS914201	**9535** *1094* *259*	**8747** *1685* *456*	**5196** *5692* *0*	**8176** *2642* *70*	469	0
UDI		**8700** *1291* *897*	**5931** *4907* *50*	**8889** *1868* *131*	117 *(group A1)*	50 *(group A2)*
BREEAM			**6303** *4524* *61*	**7801** *2215* *872*	349 *(group B1)*	61 *(group B2)*
EN17037-DF	*comply with EN17037-DF, not with EN17037-IL* ←			**7762** *3* *3123* ↓	0	2276
EN17037-IL			*comply with EN17037-IL, not with EN17037-DF*		1	3

Fig. 8. Left part: Number of rooms with identical compliance (numerals in bold), and number of rooms that are compliant with only one out of two criteria (numerals in italics). Right part: Number of rooms that comply with one criterion exclusively, and number of rooms that comply with all criteria except that criterion. Geometric attributes of rooms in groups A1, A2, and B1, B2 were compared via Mann-Whitney U-tests.

different ($|r| < 0.15$), ii) glazing area (A_G) is higher in compliant rooms but not substantially ($r < 0.25$ for all criteria), and iii) glass-to-wall ratio (GWR) is only marginally different ($|r| < 0.15$). This indicates that glazing area per se or glazing area as a ratio of façade area are not adequate predictors of daylight performance, as per the criteria considered here. On the other hand, glazing area with respect to floor area (GFR) and connection to the sky dome (VSC) are clearly different between compliant and incompliant rooms.

Comparing criteria in Table 4, EN17037-DF is the only criterion that requires smaller floor areas (A_{FLOOR}: $r = -0.31$), and less depth (D: $r = -0.40$) to yield compliance, and the only criterion for which compliance is not substantially affected by VSC ($r < 0.3$). In other words, it necessitates that rooms are smaller or that they do not extend in the building core as much as other criteria. The BREEAM criterion displays the weakest effect sizes for fenestration-related attributes (A_G: $r = 0.03$, GFR: $r = 0.34$, GWR: $r = -0.14$ and $GW_{INT}R$: $r = 0.2$), which can be explained by the fact that smaller windows can impact results more when the 0.5 m band from walls is included in the calculation. The rest of criteria (DF_P, UDI and EN17037-IL) differentiate between compliant and incompliant rooms largely due to VSC and GFR. Spearman correlation was used to follow up this finding. It appeared that the association between DF_P, UDI, BREEAM, EN17037-DF, EN17037-IL compliances and the product VSC · GFR was significantly strong (0.712, 0.703, 0.534, 0.600, 0.745 respectively, $p < 0.001$), in particular weakest for BREEAM and strongest for EN17037-IL. The latter is in agreement with the results in Fig. 4, as *F* and *G* have the highest VSC and GFR values among developments, and comply almost entirely with EN17037-IL (compliance rates, F: 100%, G: 93%).

3.7. Association with urban density

Fig. 11 shows the association between urban density and compliance per criterion (a – e). The Spearman Rank Correlation coefficient r_S in scatterplots a – e excludes *exterior circulation* developments *D, K, R* ("x"

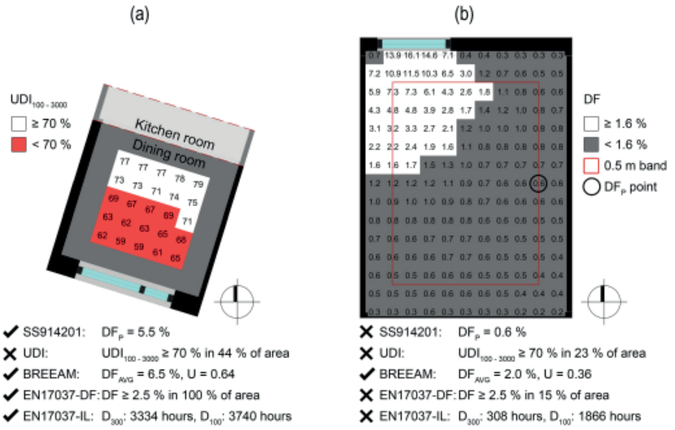


Fig. 9. A typical room design that a) complies with all criteria except UDI and b) complies exclusively with BREEAM.

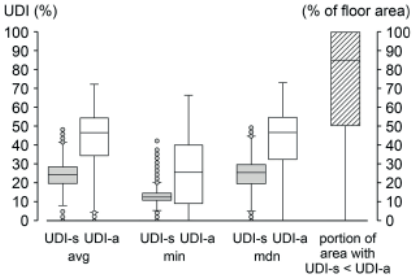


Fig. 10. Distribution of average (avg), minimum (min) and median (mdn) UDI-s and UDI-a, including all 10888 rooms. The right-most boxplot illustrates the portion of room floor area where UDI-s is lower than UDI-a.

markers), while the r_S coefficients in the right-bottom table (f) includes them. It is shown that urban density associates strongly with all criteria ($|r_S| > 0.5$, $p < 0.01$) except for EN17037-DF ($p > 0.05$). Cross-referencing this finding with the Density indicator in Fig. 1 can explain why *large courtyard blocks* and *post-modern reforms* were ranked very low by all criteria in Table 3. The strongest association occurs for UDI ($r_S = -0.820$, $p < 0.01$) and DF_P ($r_S = -0.788$, $p < 0.01$); the same is true when including *exterior circulation* developments (Fig. 11f). This indicates that compliance according to these two criteria best reflects the magnitude of surrounding obstructions, as quantified by urban density. In addition, the climate-based criterion of EN17037 is largely more responsive to surrounding obstructions compared to its daylight-factor-based counterpart (EN17037-IL: $r_S = -0.612$, $p < 0.01$, EN17037-DF: r_S not significant). The findings were followed with association tests (Spearman) between compliance and mean building height (Fig. 1, MeH). The tests revealed only one significant association, for UDI ($r_S = -0.463$, $p = 0.02$).

4. Conclusions

The choice of minimum acceptable daylight conditions sets a simple question: Is a design compliant or not? Testing compliance in a representative sample of residential rooms led to the following conclusions:

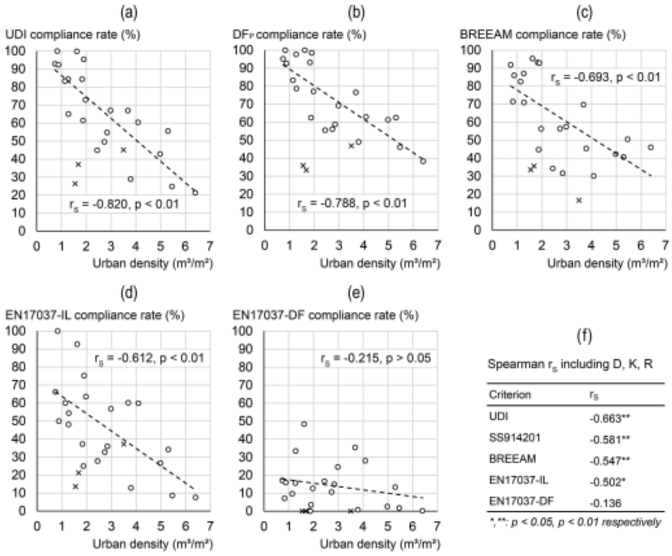
4.1. Compliance rates

Compliance was found to depend on criterion choice, however certain patterns were observed. A consistent finding was that all developments achieve very low compliance rates when tested against EN17037-DF, and higher compliance rates when tested against the current Swedish criterion SS914201. EN17037-DF in particular can be considered as unreasonably demanding, as it deemed the majority of rooms to be incompliant, even rooms in very high, unobstructed buildings set in sparsely built areas. It is important to note though that the target illumination values in the EN17037 criteria are meant to be strictly recommendations, not normative, which is why they are more

Table 4
Effect size r for comparing geometric attributes between compliant and incompliant rooms per criterion (Mann-Whitney U-tests).

	Compliance		Effect size r (for Mann-Whitney *U*-test)							
	Pass	Fail	VSC	A_{FLOOR}	D	W	A_G	GFR	GWR	$GW_{INT}R$
DF_P	7460	3428	0.61**	−0.07	−0.10	n.s.	0.16	0.42*	0.03	0.29
UDI	6625	4263	0.58**	−0.07	−0.14	0.04	0.20	0.45*	0.03	0.34*
BREEAM	6231	4657	0.46*	−0.15	−0.25	n.s.	0.03	0.34*	−0.10	0.20
EN17037-DF	1768	9120	0.26	−0.31*	−0.40*	−0.14	0.10	0.53**	0.09	0.38*
EN17037-IL	4888	6000	0.50**	−0.14	−0.19	n.s.	0.24	0.54**	0.12	0.43*

*, **: medium, large effect size respectively.
n.s.: no significant result ($p > 0.05$).



Spearman r_S including D, K, R

Criterion	r_S
UDI	-0.663**
SS914201	-0.581**
BREEAM	-0.547**
EN17037-IL	-0.502*
EN17037-DF	-0.136

*, **: *$p < 0.05$, $p < 0.01$ respectively*

Fig. 11. Spearman Rank Correlation between compliance rate and urban density per criterion (n = 25). Coefficients r_S in scatterplots (a)–(e) are calculated excluding *exterior circulation* developments *D, K, R*. The r_S coefficients in table (f) are calculated including them.

demanding. Regarding building forms, developments of *post-modern reforms*, *large courtyard* and *exterior circulation* typologies underperformed consistently, while *high-rise towers* were ranked either first or second depending on criterion. In terms of room functions, kitchens performed poorer, followed by living rooms, bedrooms and dining rooms. Dining rooms were the only function that complied in a rate higher than 50% for all criteria. This ranking contradicts occupant preferences in multi-dwelling buildings, as occupants have been shown to prioritize kitchens with respect to daylight availability, followed by living rooms, dining rooms and lastly bedrooms [3,6].

4.2. Criteria considerations

There were significant compliance similarities between the SS914201 and UDI criteria ($R^2 = 0.927$). This can be attributed to the fact that the lower illuminance limit of UDI (100 lx) has a commensurate effect on compliance as a daylight factor of 1% (DF_P threshold). A shift to a climate-based indicator for compliance testing in Sweden could consider this similarity. The UDI metric accounts for orientation and sunlight, has previously been suggested as a suitable metric for residential spaces [51], and maximizing it has been characterized as *the most reliable indicator of 'good daylight provision'* for residential buildings [52]. It can also be used in tandem with thermal comfort evaluations due to its formulation, which is particularly important as higher lighting gains may translate to higher overheating issues for residences. A notable difference was identified between the two EN17037 criteria, with the climate-based criterion yielding significantly higher compliance. This is an important finding, as it reflects the difference between daylight-factor-based and climate-based evaluations, since the two criteria are based on the same assumptions, except for sky conditions. The fact that the climate-based indicator yielded higher compliance implies that a more accurate representation of sky conditions, on an hourly basis, can reveal a different potential of a design to admit daylight, in particular a higher potential.

4.3. Effect of room geometry

The two attributes that have a meaningful effect on criteria were the Vertical Sky Component (VSC) and the glass-to-floor ratio (GFR). A deviation from other criteria was observed for EN17037-DF, for which VSC was not substantially influential, while smaller room areas and shorter depths were necessary to achieve compliance. The design decision to maximize one variable could perhaps prioritize GFR over VSC, as the former has been shown to associate with perceived brightness in residential spaces, contrary to VSC [45]. To assess the effect of "connectedness" to the sky, future work could investigate aperture-based indices, that are also aware of window size [53]. The study results also warrant against the use of the BREEAM daylight factor criterion, as it may yield compliance for rooms that are actually uniformly dark. This was the case for large, deep rooms with a window placed closer to corners than the center of the facade. Finally, the results imply that the commonly reported window-to-wall ratio (WWR) is actually not a reliable predictor of indoor daylight availability, and glass area (A_G) is a weak predictor.

4.4. Effect of urban density

Urban density was shown to be a reliable indicator of indoor daylight availability. Similarly to this, it has previously been shown to adequately predict irradiance levels on facades of urban blocks [54]. The only criterion that did not associate with urban density was EN17037-DF. Overall, the UDI criterion had a stronger connection to surroundings, as it displayed the strongest association with urban density ($r_S = -0.820$, $p < 0.01$), and was the only criterion to associate significantly with the mean building height of surroundings (p = 0.02).

Funding

This research was funded by the Swedish Energy Agency (Energimyndigheten, grant nr 41816-2), Arkus (Stiftelsen Arkus) and ARQ (c/o White Architects AB, grant nr 12:2016).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The author would like to thank Marie-Claude Dubois for helping situate the framework of this research and for contributing with important comments on the formulation of the European Standard criteria. Marja Lundgren and Malin Alenius are acknowledged for helping select representative Swedish residential buildings.

References

[1] SCB, Statistics Sweden - Swedish and foreign-born population by region, age and sex. Year 2000 - 2019. http://www.statistikdatabasen.scb.se/pxweb/en/ssd/START_BE_BE0101_BE0101E/InrUtrFoddaRegAlKon/, 2020. (Accessed 20 May 2020).

[2] Kommittén för Modernare Byggregles, (English: the building rules modernisation committee), committee terms of reference - comprehensive review of boverket's building regulations etc. http://modernarebyggregler.se/wp-content/uploads/2017/08/committee-terms-of-reference.pdf, 2017. (Accessed 16 March 2020).

[3] I. Bournas, Daylight in Swedish Multi-Dwelling Buildings: Research on the Effects of Urban Densification, Building Typology and Occupant Behavior, Center for Housing Architecture, Form Design Center, 2020. https://www.chalmers.se/SiteCollectionDocuments/Centrum/CBA/Nyheter/2020/LTH4-Iason_Bournas.pdf. (Accessed 26 February 2020).

[4] I. Bournas, M.-C. Dubois, Daylight regulation compliance of existing multi-family apartment blocks in Sweden, Build. Environ. 150 (2019) 254–265.

[5] Boverket, Boverket's Building Regulations - Mandatory Provisions and General Recommendations, BFS 2011:6 with Amendments up to BFS 2018, vol. 4, 2019. https://www.boverket.se/en/start/publications/publications/2019/boverkets-building-regulations–mandatory-provisions-and-general-recommendations-bbr/. (Accessed 17 November 2019).

[6] S. Eriksson, L. Waldenström, M. Tillberg, M. Österbring, A.S. Kalagasidis, Numerical simulations and empirical data for the evaluation of daylight factors in existing buildings in Sweden, Energies 12 (11) (2019) 2200.

[7] P. Rogers, M.-C. Dubois, M. Tillberg, M. Österbring, M. Alenius, I. Bournas, A. Larsson, M. Lundgren, M. Söderlund, V. Vakouli, Moderniserad dagsljusstandard (English: modernized daylight standard), SBUF ID: 13209, http://www.bau.se/wp-content/uploads/2018/12/SBUF-13209-Slutrapport-Moderniserad-dagsljusstandard.pdf, 2018.

[8] SBN, Svensk Byggnorm : SBN 1975 : Föreskrifter, Råd Och Anvisningar För Byggnadsväsendet Utfärdade Med Stöd Av 76§ Byggnadsstadgan, Statens planverk, 1975.

[9] SIS, Standardiseringskommissionen I Sverige - SVENSK STANDARD SS 91 42 01, 1988.

[10] P. Tregenza, M. Wilson, Daylighting: Architecture and Lighting Design, Routledge, 2011.

[11] The Building Rules Modernisation Committee, Accessed March 5 2020, http://modernarebyggregler.se/the-committee-for-modern-building-rules/, 2017.

[12] The Building Rules Modernisation Committee, Våra förslag - slutbetänkande: modernare byggregler – förutsägbart, flexibelt och förenklat (English: our proposal - final report: more modern building rules - predictable, flexible and simplified), Accessed March 5 2020, http://modernarebyggregler.se/vara-forslag/, 2019.

[13] P. Tregenza, J. Mardaljevic, Daylighting buildings: standards and the needs of the designer, Light. Res. Technol. 50 (1) (2018) 63–79.

[14] SCB, Statistics Sweden - dwelling stock 31/12/2019, Accessed, https://www.scb.se/en/finding-statistics/statistics-by-subject-area/housing-construction-and-building/housing-construction-and-conversion/dwelling-stock/, 2019. (Accessed 6 February 2020).

[15] SCB, Statistics Sweden - completed dwellings and number of rooms including kitchen in newly constructed buildings by region and type of building. Year 1975 - 2018. http://www.statistikdatabasen.scb.se/pxweb/en/ssd/START_BO_BO0101_BO0101A/LghReHustypAr/, 2019. (Accessed 8 February 2020).

[16] T. Hall, M. Rörby, Stockholm: the Making of a Metropolis, Routledge, Taylor & Francis e-Library, 2009.

[17] J. Rådberg, A. Friberg, Svenska Stadstyper : Historik, Exempel, Klassificering, Stockholm, 1996, KTH högskoletr., Stockholm, 1996.

[18] B. Grünbaum, Convex Polytopes, vol. 2, Springer, cop, New York, 2003, 2003.

[19] Stockholm Stad, Dataportalen, 3D-byggnader generalizerad (LOD1). https://dataportalen.stockholm.se/dataportalen/?SplashScreen=No, 2018. (Accessed 15 February 2020).

[20] ESRI, ArcGIS ArcMap, 2016.

[21] V.5 Rhinoceros, Robert McNeel and Associates, 2018.

[22] Grasshopper, Algorithmic Modelling for Rhino, Robet Mcneel and associates, 2018.

[23] Stockholm stad, Bygg och plantjänsten. https://etjanster.stockholm.se/byggochplantjansten/pagaende-planarbete/planarende/2018-09912, 2018. (Accessed 19 January 2020).

[24] Boverket, Boverket's Building Regulations - Mandatory Provisions and General Recommendations, 2018, p. 98. BFS 2011:6 with amendments up to BFS 2018:4.

[25] C.F. Reinhart, Daylight Handbook II, Building Technology Press2018.

[26] W.L. Greg, S. Rob, Rendering with Radiance: the Art and Science of Lighting Visualization, Morgan Kaufmann Publishers Inc., 1998.

[27] M. Sadeghipour Roudsari, M. Pak, Ladybug: a parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design. Proceedings of the 13th International IBPSA Conference Held in Lyon, France, 2013, pp. 3128–3135.

[28] D. Jarvis, M. Donn, Comparison of Computer and Model Simulations of a Daylit Interior with Reality, IIBPSA/Building Simulation, Prague, Czech Republic, 1997, 1997.

[29] J. Mardaljevic, Validation of a lighting simulation program under real sky conditions, Light. Res. Technol. 27 (4) (1995) 181.

[30] S. Subramaniam, R. Mistrick, A More Accurate Approach for Calculating Illuminance with Daylight Coefficients, The IES Annual Conference, Portland, 2017. Oregon, USA, 2017.

[31] D. Bourgeois, C.F. Reinhart, G. Ward, Standard daylight coefficient model for dynamic daylighting simulations, Build. Res. Inf. 36 (1) (2008) 68–82.

[32] CEN, European Standard EN 17037:2018 Daylight in Buildings, 2018, p. 77.

[33] IES, LM-83-12, Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), Illuminating Engineering Society, New York, US, 2012, p. 14.

[34] CIE/ISO, Spatial Distribution of Daylight e CIE Standard General Sky, 2004. ISO 15469:2004 (E)/CIE S011.

[35] A. Nabil, J. Mardaljevic, Useful daylight illuminance: a new paradigm for assessing daylight in buildings, Light. Res. Technol. 37 (1) (2005) 41–57.

[36] J. Mardaljevic, M. Andersen, N. Roy, J. Christoffersen, Daylighting Metrics: Is There a Relation between Useful Daylight Illuminance and Daylight Glare Probabilty?, Building Simulation and Optimization Conference BSO12, Loughborough, UK, 2012.

[37] SGBC, BREEAM-SE 2017 1.1, Sweden Green Building Council, 2017, p. 432.

[38] US Department of Energy DOE. https://energyplus.net/weather/simulation, 2019. (Accessed 27 April 2020).

[39] J. Mardaljevic, J. Christoffersen, 'Climate connectivity' in the daylight factor basis of building standards, Build. Environ. 113 (2017) 200–209.

[40] M.L. McHugh, The Chi-square test of independence, Biochem. Med. 23 (2) (2013) 143–149.

[41] J. Cohen, Statistical Power Analysis for the Behavioral Sciences, second ed., Lawrence Erlbaum Associates, New York, 1988.

[42] G.V. Glass, K.D. Hopkins, Statistical Methods in Education and Psychology, third ed., Allyn and Bacon, Boston, 1995.

[43] P. Littlefair, Site layout planning for daylight and sunlight - a guide to good practice. Building Research Establishment, IHS BRE Press, Watford, 1991.

[44] P. Littlefair, Daylight, sunlight and solar gain in the urban environment, Sol. Energy 70 (3) (2001) 177–185.

[45] I. Bournas, M.-C. Dubois, T. Laike, Perceived daylight conditions in multi-family apartment blocks – instrument validation and correlation with room geometry, Build. Environ. 169 (2019) 106574.

[46] H.B. Mann, D.R. Whitney, On a test of whether one of two random variables is stochastically larger than the other, Ann. Math. Stat. 18 (1) (1947) 50–60.

[47] C.O. Fritz, P.E. Morris, J.J. Richler, Effect size estimates: current use, calculations, and interpretation': correction to Fritz et al, 2012, J. Exp. Psychol. Gen. 141 (1) (2011), 30-30.

[48] H. Coolican, Research Methods and Statistics in Psychology, fifth ed., Hodder Education Group, London, United Kingdom, 2009.

[49] M. Spitzer, J. Wildenhain, J. Rappsilber, M. Tyers, BoxPlotR: a web tool for generation of box plots, Nat. Methods 11 (2) (2014) 121–122.

[50] J. Mardaljevic, J. Christoffersen, A Roadmap for Upgrading National/EU Standards for Daylight in Buildings, CIE Midterm Conference – towards a New Century of Light, Paris, France 12-19 April, 2013.

[51] J. Mardaljevic, M. Andersen, N. Roy, J. Christoffersen, Daylighting Metrics for Residential Buildings, 27th Session of the CIE, Sun City, South Africa, July 11-15, 2011, 2011.

[52] J. Mardaljevic, Climate-based Daylight Analysis for Residential Buildings, Technical Report, IESD, De Montfort University, Leicester, 2008.

[53] J. Mardaljevic, N. Roy, Envelope First/inside Later: Aperture Sunlight and Skylight Indices, 2017.

[54] C. Chatzipoulka, R. Compagnon, M. Nikolopoulou, Urban geometry and solar availability on façades and ground of real urban forms: using London as a case study, Sol. Energy 138 (2016) 53–66.

Paper 4

Building and Environment 169 (2020) 106574

Contents lists available at ScienceDirect

Building and Environment

journal homepage: http://www.elsevier.com/locate/buildenv

Perceived daylight conditions in multi-family apartment blocks – Instrument validation and correlation with room geometry

Iason Bournas [a,*], Marie-Claude Dubois [a], Thorbjörn Laike [b]

[a] Energy and Building Design, Department of Architecture and the Built Environment, Lund University, Box 118, SE-221 00, Lund, Sweden
[b] Environmental Psychology, Department of Architecture and the Built Environment, Lund University, Box 118, SE-221 00, Lund, Sweden

A R T I C L E I N F O

Keywords:
Daylight
Perception
Brightness
Residential environment
Room geometry

A B S T R A C T

This article investigates the relation between subjective evaluations and objective measurements of daylighting in multi-family residential buildings. More specifically, the suitability of an observer-based environmental assessment (OBEA) instrument to assess indoor daylight conditions was tested in a field study conducted in six typical multi-family apartment buildings in the central and metropolitan area of Malmö (Latitude: 55.6 °N), Sweden. The OBEA used self-administered questionnaires based on bipolar semantic scales aiming to capture two perceived daylight qualities: brightness and distribution. Following a factorial approach, one component pertaining to perceived brightness was deducted ("Brightness", Cronbach's alpha $= 0.89$) and validated by associating it with outdoor global horizontal irradiance (Spearman's $r_S = 0.566$, $p = 0.006$), which was monitored during the survey. Subsequently, this component was correlated with key geometric attributes of the investigated apartments to highlight the most important associations between perceived brightness and room geometry. Results indicate that the OBEA displays high internal reliability for the derived component, and is fit for daylight perception evaluations in residential spaces. In addition, the analysis showed a tendency for variables pertaining to window size to associate with perceived brightness, but also contributing to this association was the level of global horizontal irradiance.

1. Introduction

In the field of illumination engineering, recommendations on "adequate" daylight conditions have mostly emphasized on increasing visual performance, with the intent to facilitate visual tasks in order to reduce electric lighting use [1]. This is reflected in the current definition of daylight performance indicators (metrics) proposed by standards and certification systems, where metrics indeed measure the time "when illuminance is provided by daylight alone" while ensuring "a minimum amount of illumination" for a given task or space [2,3]. Such evaluations are then implying that specific photometric benchmarks are related to occupant health and well-being [4]. The traditional parameter in such evaluations is illuminance on the horizontal plane, the height of which is a proxy of the height where a task is conducted (e.g. height of a workstation).

On the other hand, a behaviorally-based definition of lighting quality incorporates multiple requirements for a luminous environment, such as visual and post-visual performance, social interaction and communication, mood state, health, safety and aesthetic judgements [5]. These can be quantified by means of instruments from the field of environmental psychology [6], but are harder to assess at the design phase before the building is complete. Nevertheless, we can deduct knowledge from existing spaces to apply in future developments, e.g. compare subjective evaluations of luminous environments with objective measurements of photometry or geometry and derive benchmark values (e.g. minimum acceptable illuminances or glass-to-floor ratios) according to occupant perception.

Prior to comparing objective with subjective output, one needs to initially establish an observer-based assessment tool, an "instrument", with which to "measure" subjective evaluations. A first attempt was made by Flynn in 1977 [7], who suggested that perception of lighting could be captured by bipolar semantic scales [8]. Based on this work, Küller and Wetterberg [9] used ten bipolar adjectives such as *Bright – Dark*, *Strong – Weak* etc. to capture human experience of the luminous environment. These adjective pairs have been used in a number of laboratory and field studies since then, to capture the experience of different working environments [10], to test effects of electric lighting installations within educational facilities [11] and outdoor urban paths

---

* Corresponding author. Lund University, Department of Architecture and the Built Environment, P.O. Box 118, SE 22100 Lund, Sweden.
E-mail address: iason.bournas@ebd.lth.se (I. Bournas).

https://doi.org/10.1016/j.buildenv.2019.106574
Received 18 October 2019; Received in revised form 20 November 2019; Accepted 28 November 2019

[12], and to evaluate electric lighting use of office workers [13] in different seasons. In the present paper, we evaluated the suitability of specific scales for the assessment of perceived lighting quality in residential spaces, with daylight as the sole illuminant.

Focusing on aesthetic judgements, we conducted a field study that incorporates daylight quality assessments in residential spaces, deduced from scale measurements for the impression of two qualities: brightness and distribution. Relying on an observer-based environmental assessment (OBEA) instrument [12], we surveyed occupant opinions on their own visual perception of their apartments. The OBEA incorporated seven semantic differential scales, which we eventually reduced to one interpretable component for perceived brightness. The component was tested for its reliability and validity as an assessment tool, and was associated with key room geometric attributes.

1.1. Objective

The study had a two-fold objective: Firstly, to evaluate whether the OBEA instrument is suitable for measuring perceived brightness and daylight distribution in typical apartment rooms. This part included a reliability analysis and a validation study for the OBEA measurement. The second objective was to test correlations between the OBEA output and room geometry, to find the most important geometric attributes associated with perceived brightness. This part included statistical association between the validated OBEA measurement and typical room geometric dimensions.

2. Methodology

2.1. Sampled buildings

The work was carried out in a field study that included six different residential buildings located in the city of Malmö (Latitude: 55.6 °N), Sweden. The buildings, shown in Fig. 1, include multi-family apartments, which are the most popular type of dwelling in Sweden (51 %) [14]. The blocks were selected based on their relevance to typical examples of Swedish urban planning history [15,16], with the aim to represent residential sector designs. The typical floor plans are shown below each aerial view. Following the specifications for lighting recommendations in the Swedish building code [17], the investigated rooms only included spaces where people stay more than occasionally: bedrooms (B), living rooms (L) and kitchens (K). Different typologies have different plan layouts and room geometries, which created a rich architectural database, i.e. the database included rooms with great variation in area size, shape, depth, fenestration and obstructions (e.g. balcony).

2.2. Building models

To derive room and fenestration dimensions, apartment plans of the selected buildings were modelled according to documentation drawings retrieved from Malmö City Planning Office [18]. Validation of the detailed apartment dimensions was conducted via on-site measurements of at least three apartments per building, which was adequate in order to derive accurate geometric attributes for each of the different apartment layouts. To assess the effect of surroundings, surrounding objects were designed as LOD2 volumes. Their building footprints were retrieved in vector format [19] and combined in ArcGIS ArcMap [20] with the latest LiDAR data (point density = 0.5–1.0 points/m^2) available from Swedish Surveying and Cadastral Agency [21] to model 3D volume geometries. These geometries were culled in a 200 m radius from the investigated buildings, using the visual programming environment of Grasshopper [22]. The culling procedure is described in detail elsewhere [23].

2.3. Geometric attributes and global horizontal irradiance (GHI) measurement

The geometric attributes surveyed were seven typical dimensions of any room in residential architecture, which can be used to formulate simplified design guidelines: the glazing area (A_G), the floor area (A_{FLOOR}), the glass-to-wall ratio (GWR), the glass-to-floor ratio (GFR), the glass-to-interior-surfaces-area ratio ($GW_{INT}R$), which is the glazing area relative to the sum of interior wall areas, the number of fenestrated walls (nW_{WIN}) and the room depth (D). Reflectances for the main room surfaces (walls, floor and ceiling) were not considered for this study, as they could not be retrieved for all investigated rooms. However they were measured in 45 rooms (where permission was granted for measurements), by means of a Konica Minolta CM-600d portable spectrophotometer. A summary of these measurements is shown in Fig. 2. The interquartile ranges of the wall, floor and ceiling reflectance distributions are shown to lie between typically recommended values [2]. A preliminary association of these measurements with occupant responses on perceived brightness did not reveal any significant association, however no further data processing regarding reflectance values was conducted to test further associations (e.g. deriving room average area-weighted reflectance).

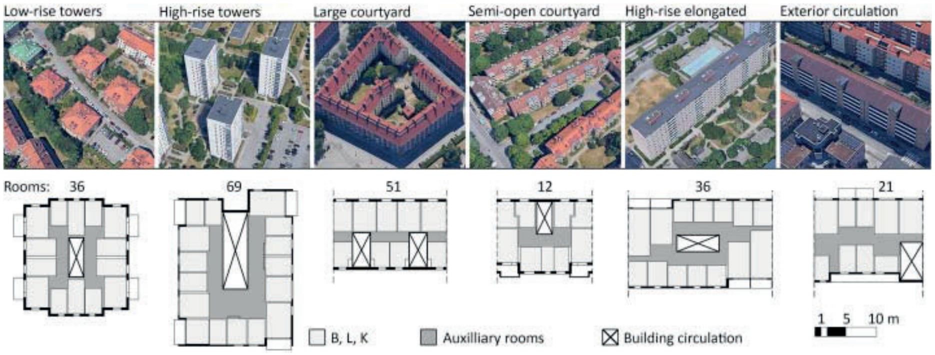


Fig. 1. Aerial view, number of evaluated rooms and typical floor plans of surveyed buildings. Aerial images © Landsat/Copernicus and Data S O, NOAA, U.S. Navy, NGA, GEBCO.

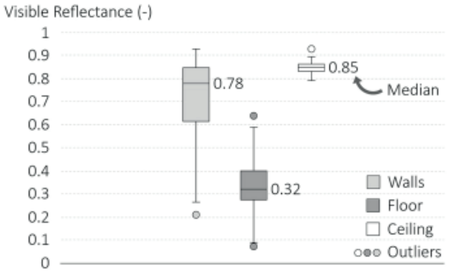


Fig. 2. Distributions of visible reflectance for walls, floors and ceilings, measured in 45 rooms.

To test the association between perception and surrounding obstructions, the Vertical Sky Component (VSC) was calculated for each room. According to Littlefair, VSC is "the ratio of that part of illuminance, at a point on a given vertical plane, that is received directly from a CIE standard overcast sky, to illuminance on a horizontal plane due to an unobstructed hemisphere of this sky"…"The VSC does not include reflected light, either from the ground or from other buildings" [24]. The vertical plane in the present study was the room window, and VSC was calculated as the average value of a grid of point VSC measurements on the outer glazing surface (grid density 0.1 m). For rooms comprising more than one windows, Littlefair [24] suggests that the average of their VSCs may be calculated, when the windows are equally sized. Since in this study windows were not always equally sized, in cases of rooms with two or more windows, the glazing-area-weighted average VSC of windows was calculated as the overall room VSC value. It should be noted here that the VSC definition assuming a CIE Overcast Sky and only considering direct skylight deviates from the conditions in the present study, as occupants did not necessarily respond under such a sky and their rooms were also illuminated by daylight reflected off from surrounding obstructions and the ground. Radiance [25] via Honeybee [26] was used to derive VSC using an –ad rendering setting of 16384 to sample enough rays towards the sky dome in order to account more accurately for urban obstructions.

The global horizontal irradiance was measured during the survey to record weather information in order to validate the OBEA. Measurements were taken using a Kipp&Zonen CM-11 pyranometer, which was calibrated shortly before the experimental study and installed on a centrally located, unobstructed roof. A data-logger was programmed to record irradiance values every minute, where each minute log was the arithmetic mean of six measurements, each one taken every 10 s. As participants were asked to report the exact time when they filled in the questionnaire in Month: Day: Hour: Minute format (MM: DD: HH: mm), the global horizontal irradiance during their participation could be derived. The GHI variable reported in this paper is the arithmetic mean of 5 min-logs, as the questionnaire procedure was estimated to last approximately 5 min.

2.4. Survey subjects

The participants were contacted via regular mail sent to their civic addresses. No specific selection aimed at age or gender distribution was made a priori for the sample, although the number of participants (= 75) led to sufficient variation, as was confirmed during post-processing. The questionnaire was sent in three different languages, namely Swedish, English and Arabic, with the intent to increase the response rate, as foreign-born citizens between ages 18 and 77 corresponded to 40 % of the city population at the time of the survey, according to Statistics Sweden [27]. Nevertheless, all participants used the Swedish language, so the main cultural background of participants can reasonably be assumed to be Swedish. The questionnaire was sent out to 945 apartments, and 108 returned their answers. Another 87 questionnaires were automatically sent back by the postage service since their recipients had moved out. The final response rate was thus calculated to 13 %. The low response rate can be attributed to the fact that no follow-up reminders were sent, and no monetary incentive or other retribution was offered for participation. However the age of participants, which is by far the most common cause of limited visual capacity [28], was found to be satisfactorily distributed, as shown in Fig. 3. Gender participation was 60 % women and 40 % men. Of the 108 filled questionnaires, 28 had to be discarded from the statistical analysis due to missing values, and 5 were discarded because they corresponded to small apartments that did not include all three different room types (K, L, B). The final sample therefore included 75 respondents, corresponding to 75 different apartments that included 225 rooms (sample S_{225}, N = 225). It should be noted here that sample size per building differed (Fig. 1), due to the study design, which involved using self-administered questionnaires. This led to a random number of participants per building type.

2.5. Date and time of survey

The questionnaires were distributed on March 13, 2018, to ensure they would be filled in during a period as close to spring equinox as possible. The equinox is representative of an "average day" in daylight studies since it provides i) balance between nighttime and daytime, ii) yearly average solar elevations per hour and as a consequence iii) average shadow lengths. It is therefore prescribed by lighting monitoring protocols as a test day [29]. The vast majority of questionnaires (90 %) were filled within a week from the spring equinox, as shown in Fig. 4. The majority of questionnaires (73 %) were filled in between 9:00 and 15:00 h. In some cases two or more apartments participated simultaneously, which is indicated by the size of the circular markers.

2.6. Procedure and instrument

The participants were asked to start filling the questionnaire after reading specific instructions, which prompted them to: i) be inside the specific room while filling items corresponding to that room, ii) answer during daytime (sun above the horizon), iii) switch off electric lighting prior to answering and iv) fully retract any shading device (e.g. curtains, blinds) prior to answering. Table 1 shows the scales used for each of the three room types, where the participants were asked "How would you describe the daylight in the [*room type*] right now?". As previously mentioned, the perceived lighting qualities were assessed using seven-grade bipolar rating scales that are based on earlier work by Küller

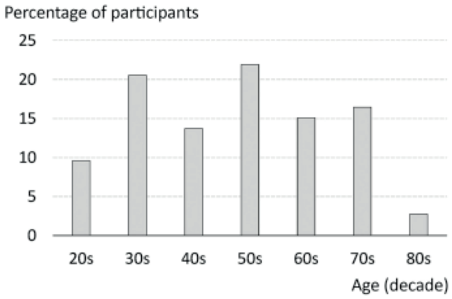


Fig. 3. Percentage distribution of participants' age.

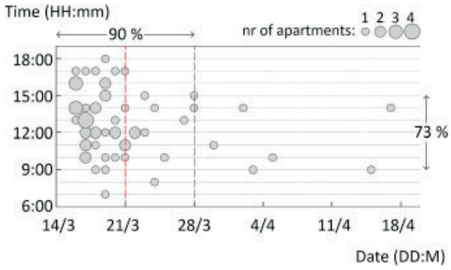


Fig. 4. Date and time of participation, and number of apartments per 1-h timespan.

Table 1
Bipolar seven-grade scales used.

Scale
Dark - Light *(1)*
Scattered - Concentrated *(2)*
Clear - Drab *(1)*
Uneven distributed - Even distributed *(2)*
Strong - Weak *(1)*
Unfocused - Focused *(2)*
Subdued - Brilliant *(1)*

(1) Scales intended to capture perceived brightness
(2) Scales intended to capture perceived distribution

and Wettenberg [9,10], with the intent to capture two dimensions: brightness (4 scales, indicated by "*(1)*" in Table 1) and distribution (3 scales, indicated by "*(2)*" in Table 1). The bipolar adjectives shown in Table 1 are semantic differentials that have previously been developed in the Swedish language, making them suitable in the context of Swedish culture. They are shown here translated in English, in the same order and direction as they were included in the distributed questionnaire. After the exploratory factor analysis presented in section 3.1, only the scales related to brightness (4 scales) were retained, and were averaged to a single index (Brightness) ranging from 1 (low brightness) to 7 (high brightness) for each participant. This index was used to examine the relation between perceived brightness and room geometry.

Since the questionnaire was self-administered, clarifications needed to be made in order to ensure that participants would answer for the intended areas within their apartments. For kitchens, in the case that a distinct dining room area existed, the occupants were asked to discard it and to evaluate the space in the meal preparation area (close to kitchen cabinets). For the bedroom, participants were asked to answer for the largest one in case an apartment had several bedrooms. It should be noted here that the questionnaire did not include specific instructions regarding positioning in space and view direction. This choice was made in order to avoid uncertainty due to unreliable data from occupants assuming wrong positions or facing towards a different direction than the one dictated, given that no interviewer was present at the time of participation to guide them. This constitutes a limitation of the present study. The intention was for occupants to report an overall judgement of the lighting conditions, instead of an assessment of a fixed field of view. This effectively implies that multiple view directions could have been deployed by the occupant, examining multiple parts of the space prior to responding. In essence, this does not affect the factor analysis on the questionnaire scales, but could affect results pertaining to the association of occupant responses with geometric attributes. Uncertainty regarding the latter case would be amplified if occupants of different rooms deployed completely different view directions with respect to their room geometry (e.g. one occupant standing under the room door staring towards the fenestration and another standing in front of the fenestration and staring towards the back end of the room).

2.7. Room samples and data processing

The different statistical tests performed and the corresponding room samples and variables are shown in Table 2. The first step included processing data of the overall room sample S_{225} (N = 225), which corresponds to the 75 different apartments/participants. For this sample, a Principal Component Analysis (PCA) was performed on the seven bipolar scales with orthogonal rotation (varimax), with a requirement of eigenvalues > 1, to eventually derive one component (Brightness) pertaining to perceived brightness. Cronbach's alpha was calculated to evaluate the internal reliability of Brightness.

To assess the validity of the derived component Brightness, Spearman Rank Correlation (SRC) was performed with GHI. For this part, only rooms of the "high-rise elongated" building type were considered, as this building consisted of multiple identical rooms (equal geometric attributes) with nearly identical surrounding obstructions (VSC: M = 36.71, SD = 3.29), making it possible to isolate the effect of GHI on Brightness. This sample of 24 rooms (sample S_{BK}, N = 24) included the bedrooms and kitchens of the apartments. Living rooms were excluded as they were considerably deeper and had a balcony obstruction, while kitchens and bedrooms were identical in geometry.

For the association of Brightness with geometry, non-parametric tests were used due to lack of normality in the distribution of all variables. SRC was used for all geometric attributes, in three different samples: i) the overall room sample S_{225}, ii) the sample of rooms that only had one window and no balcony (sample S_I, N = 157), and iii) the sample of rooms that only had one window and had a balcony above it (sample S_{II}, N = 41). These samples (S_I, S_{II}) were manually categorized to test the influence of the balcony obstruction as a confounding factor in the associations between perception and geometry. Fig. 5 provides statistical information on the geometry of rooms included in each of the samples S_{225}, S_I, and S_{II}, with standard deviations (SD) and average (M), minimum (min) and maximum (max) values for each geometric attribute. Median values (Mdn) and outliers (circular markers) per attribute can be derived from the boxplots. According to Fig. 5, significant differences between samples S_I and S_{II} in terms of room geometry include

Table 2
Statistical tests performed with corresponding samples, sample sizes and variables.

Test	Sample	Size	Variable
Factor analysis (PCA and reliability analysis)	S_{225}[a]	N = 225	Questionnaire scales
Validation (Spearman rank correlation)	S_{BK}[b]	N = 24	GHI
Association with geometric attributes (Spearman rank correlation)	S_{225}	N = 225	VSC, A_G, A_{FLOOR}, GWR, GFR, $GW_{INT}R$, nW_{WIN}, D
	S_I[c]	N = 157	
	S_{II}[d]	N = 41	
Association with benchmarks (Mann-Whitney *U* test)	S_{225}	N = 225	VSC: [0, 20) and [20, 40][e] GFR: [0, 10) and [10,20][e] GHI: [0, 300) and [300, 600][e]

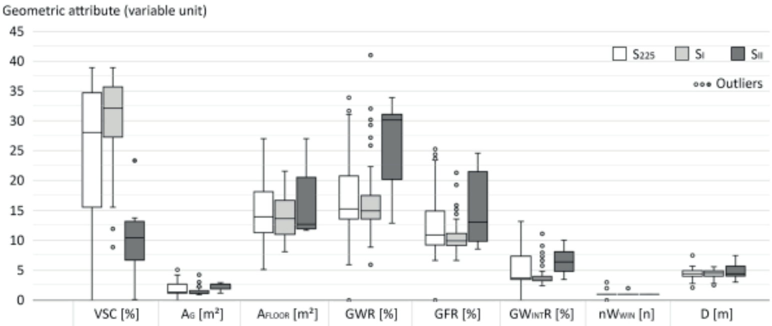
[a] The overall room sample (all investigated rooms included).

[b] Sample of identical rooms in terms of geometry and surrounding obstructions (from "high-rise elongated" building).

[c] Sample of rooms with a single opening and without a balcony (out of all rooms).

[d] Sample of rooms with a single opening and a balcony obstruction above it (out of all rooms).

[e] The two domains in which variables were manually dichotomized ("[" includes value, "(" does not include value).



	VSC [%]			AG [m²]			AFLOOR [m²]			GWR [%]			GFR [%]			GWINTR [%]			nWWIN [n]			D [m]		
M	25.3	31.1	9.9	1.9	1.5	2.4	14.9	14.1	16.0	18.3	17.0	26.8	12.5	10.9	12.5	5.1	4.2	6.7	1.1	1	1	4.4	4.4	4.7
SD	10.8	6.1	4.2	1.0	0.7	0.6	4.4	3.6	5.2	7.7	6.3	7.2	4.9	2.9	4.9	2.7	1.7	2.3	0.4	0	0	0.9	0.7	1.3
min	0	8.9	0.1	0	0.9	1.2	5.2	8.1	11.7	0	5.9	12.9	0	6.7	0	0	2.4	3.5	0	1	1	2.1	2.5	3.0
max	38.9	38.9	23.3	5.1	4.3	3	27.0	21.6	27	41	41	33.9	25.3	21.3	25.3	13.2	11.1	10	3	1	1	7.5	5.6	7.5

Fig. 5. Summary of room characteristics for samples S_{225}, S_I, and S_{II}, with standard deviations (SD) and average (M), minimum (min) and maximum (max) values of the studied geometric attributes.

attributes pertaining to window area and room vertical surfaces: S_{II} rooms have i) significantly lower VSCs (S_I: Mdn = 32.1 %, S_{II}: Mdn = 9.9 %), ii) significantly higher A_{GS} (S_I: Mdn = 1.3 m^2, S_{II}: Mdn = 2.7 m^2), iii) significantly higher GWRs (S_I: Mdn = 15.0 %, S_{II}: Mdn = 30.1 %) and iv) significantly higher GW_{INT}Rs (S_I: Mdn = 3.6 %, S_{II}: Mdn = 6.4 %). This indicates that S_{II} rooms have a broader view out, but this view is not necessarily exposed to the sky dome, compared to S_I rooms. This effectively means that they have larger glazing areas covering their facades, but these glazing areas are not as bright as the glazing areas of S_I rooms. No significant differences were found between samples S_I and S_{II} in terms of A_{FLOOR}, GFR, D, and GHI. The balcony depth for rooms in sample S_{II} did not vary significantly, ranging from 1.3 m to 1.6 m, with five outliers, one at 0.6 m and four at 2.0 m depth. For statistical information on occupant responses per questionnaire scale for samples S_{225}, S_I, and S_{II}, the reader is referred to Fig. 6. Visually inspecting the distributions of the different questionnaire scales, it is evident that "distribution" scales (scales 2, 4 and 6) are significantly different, for all room functions (K, L, B), already indicating low internal reliability for this factor.

Finally, the Mann-Whitney *U* test (MWU) was used to evaluate if Brightness differs significantly between subgroups of VSC, GWR and GHI in the overall room sample (S_{225}). For this test, each variable was transformed into a binary categorical variable (0 or 1). The two domains are shown for each variable in Table 2, where "[" denotes that the domain start or end value is included and "(" that it is excluded. The division into two domains was made using specific benchmark values, in order to test whether there are significant differences in light perception between the groups above or below these benchmarks. The VSC benchmark value used was 20 % (domains [0–20), [20–40]), as VSC values in excess of 20 % within urban areas *should be considered as reasonably good* [30]. The GFR benchmark of 10 % was used as it is recommended in the Swedish building code [31] as well as in many other national standards and regulations for the provision of daylight in residential spaces [32]. The GHI was dichotomized based on its mid-range, which is the arithmetic mean of the maximum and minimum recorded values. All tests were performed using SPSS Statistics 24, and in all tests results were considered statistically significant for p values < 0.05.

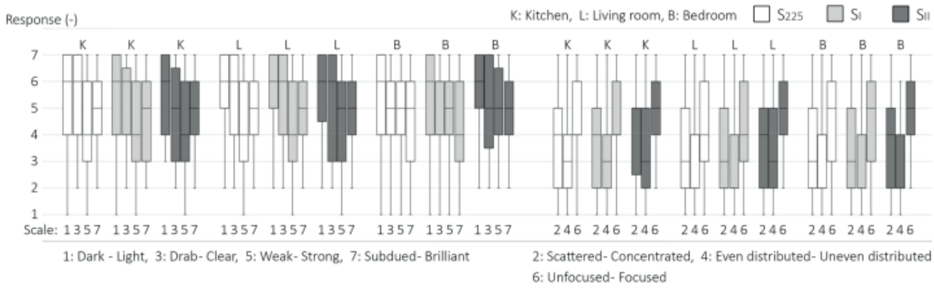


Fig. 6. Distributions of questionnaire scales per room function (K: Kitchen, L: Living room and B: Bedroom) for samples S_{225}, S_I and S_{II}. Questionnaire scale numbers are shown below each boxplot, where scales 1, 3, 5 and 7 pertain to perceived brightness, and scales 2, 4 and 6 to perceived distribution. Scales 3, 4, and 5 have been reversed (compared to Table 1).

3. Results

3.1. Exploratory factor analysis

For the sample of all assessed rooms (sample S_{225}, N = 225), all seven scales in the questionnaire were found to be normally distributed in a satisfactory degree, as the ratio of skewness and kurtosis to their standard errors did not exceed 5 in any case. Principal Component Analysis (PCA) was performed using orthogonal rotation (varimax), extracting components based on eigenvalues > 1. This approach was supported by the KMO measure (= 0.838) indicating *meritorious* sampling adequacy according to Kaiser and Rice [33], and by Bartlett's Test of Sphericity (x^2 (21) = 734.522, $p < 0.001$). The PCA identified two components that are shown in Table 3, intended to capture Brightness and Distribution. One scale loaded on both components (Unfocused – Focused, 0.487 brightness and 0.684 distribution). The same scale has actually been shown to load highly in the Brightness component in a previous study that concerned perceived outdoor lighting qualities using electric light sources [12]. A counter-intuitive result is that scale "Even distributed – Uneven distributed" loaded on the Brightness component (0.667) instead of the Distribution. Since the Distribution component only consisted of two scales, Spearman's Rank Correlation was tested (instead of Cronbach's alpha) to evaluate its reliability. This association was found rather weak ($r_S = 0.251$, $p < 0.01$). On the other hand, the Brightness component was shown to explain 52.29 % of the variance and to be satisfactorily composed by four scales that loaded high (all loadings > 0.80). In addition, Cronbach's alpha for the Brightness scales was 0.89, suggesting high internal reliability for the component. The study therefore proceeded with this component for associations with geometry, by averaging for each participant the 4 scales into one index, Brightness, M = 4.95, SD = 1.38, range: 1–7.

3.2. Instrument validation

For the validation of the derived Brightness component, the responses from occupants of the "High-rise elongated" building were utilized, assessing the maximum amount of identical rooms in terms of geometry and surroundings (S_{BK}, N = 24 rooms). For theses rooms, the Spearman Rank Correlation between Brightness and GHI was strong ($r_S = 0.566$, $p = 0.006$) indicating that the Brightness component has the intended content validity.

3.3. Associations between OBEA and geometric attributes

The association of Brightness with room geometry and VSC is shown in Table 4. Spearman's r_S and p values are shown for three samples: the overall room sample (S_{225}, N = 225), the S_I sample (N = 157) and the S_{II} sample (N = 41). The latter two samples consist of rooms with one window, where S_I rooms do not have a balcony while S_{II} have one. For S_{225}, the attributes pertaining to window size are very weakly correlated with Brightness, namely A_G ($r_S = 0.145$, $p < 0.05$), GWR ($r_S = 0.144$, $p < 0.05$) and $GW_{INT}R$ ($r_S = 0.135$, $p < 0.05$. No significant associations were found for the S_I rooms (rooms without a balcony). On the other hand, for the S_{II} rooms, there is moderate correlation between Brightness and A_G ($r_S = 0.455$, $p < 0.005$), GFR ($r_S = 0.419$, $p < 0.01$) and $GW_{INT}R$ ($r_S = 0.455$, $p < 0.005$), and a weak correlation with GWR ($r_S = 0.356$, $p < 0.05$).

Table 3
Exploratory factor analysis (S_{225}, N = 225) with mean values (M), standard deviations (SD) and factor loadings (in bold) for Brightness and Distribution.

Scale	Distribution		Rotated factor loadings (varimax)	
	M	SD	Brightness	Distribution
Weak - Strong	4.52	1.64	**0.864**	0.070
Subdued - Brilliant	4.71	1.52	**0.860**	0.254
Dark - Light	5.46	1.51	**0.856**	0.079
Drab - Clear	5.10	1.68	**00822**	−0.087
Scattered - Concentrated *(excluded, low r_s)*	3.43	1.83	−0.237	**0.864**
Unfocused - Focused *(excluded, low r_s)*	4.48	1.54	0.487	**0.684**
Even distributed - Uneven distributed (*excluded*)	3.03	1.65	−0.667	0.239
Percentage of variance			52.29	18.99
Eigenvalues			3.661	1.329
Cronbach's alpha			0.89	
Spearman's r_S				0.251 ($p < 0.01$)

At first glance, Table 4 indicates that a balcony obstruction deems window-related attributes more important in terms of perceived brightness, as these attributes are associated more strongly with Brightness for S_{II} rooms, compared to S_I rooms. These attributes were also significantly different between the two samples (Fig. 5). Further analysis was conducted to test whether this assumption for S_{II} rooms is true for any sky condition, as GHI was previously shown to associate strongly with perceived brightness (section 3.2). Firstly, for each of the associated attributes (A_G, GWR, GFR and $GW_{INT}R$), S_{II} rooms were subdivided into two groups, according to the median value of each attribute (A_G: Mdn = 2.7 m^2, GWR: Mdn = 30.1 %, GFR: Mdn = 13.1 % and $GW_{INT}R$: Mdn = 6.4 %). The GHI distributions between groups in each pair were then compared. The comparison (Fig. 7) shows that the groups with higher attribute values (white boxplots) have higher GHI values. In other words, considering e.g. A_G, there was more global horizontal irradiance (W/m^2) available when responses for rooms with larger windows were given. This indicates that GHI acts as a confounding factor in the association of Brightness with geometry in S_{II} rooms. Finally, to eliminate the effect of GHI, S_{II} rooms were subdivided into three bins according to GHI ranges of 0–200, 200–400 and 400–600 (W/m^2) and SRC was performed between Brightness and A_G, GWR, GFR and $GW_{INT}R$ for each individual bin. No significant association was revealed for any bin, which verifies that geometric attributes alone did not affect perceived brightness, but rather they affected it in conjunction with GHI. Similarly, performing SRC between Brightness and geometric attributes for each GHI bin in S_I rooms did not reveal any significant correlation.

3.4. Associations between OBEA and VSC, GFR, GHI benchmarks

Finally, to evaluate if Brightness varies significantly between subgroups of VSC, GFR and GHI, the Mann-Whitney *U* test was performed for the overall room sample S_{225}. Each variable was dichotomized into two subgroups based on the benchmark values previously stated in Table 1. The test indicated that Brightness was significantly higher when GFR ranged between 10 % and 20 % (Mdn = 5.25) compared to GFR ranging between 0 % and 10 % (Mdn = 4.50), U = 7358.5, p = 0.02. Brightness was also found significantly higher when GHI ranged between 300 W/m^2 and 600 W/m^2 (Mdn = 5.5) compared to GHI ranging between 0 W/m^2 and 300 W/m^2 (Mdn = 4.75), U = 5373, p = 0.004. Finally, the test indicated that rooms with VSC higher than 20 % did not report significantly higher Brightness compared to rooms with low VSC (lower than 20 %). Following on the latter finding, the data were processed to identify any other VSC benchmark value based on perceived brightness: the overall room sample S_{225} was dichotomized into two subgroups seven times, each time based on a different VSC value (5, 10, 15, 20, 25, 30 and 35). Each time the two subgroups were compared by comparing their median Brightness values via a Median Test. Following seven tests, no significant differences between groups were found, thus no such VSC benchmark value could be established.

4. Discussion

The work carried out during this study presented a number of novel

Table 4
Spearman's Rank Correlation between Brightness and geometric attributes for samples S_{225}, S_I and S_{II}.

Sample		VSC	A_G	A_{FLOOR}	GWR	GFR	$GW_{INT}R$	nW_{WIN}	D
S_{225}	r_S	0.096	0.099	0.014	0.145*	0.144*	0.135*	0.010	−0.027
	p	0.151	0.140	0.830	0.030	0.030	0.043	0.879	0.682
S_I	r_S	0.108	0.096	0.042	0.114	0.115	0.146	–	−0.057
	p	0.177	0.230	0.600	0.156	0.152	0.068	–	0.475
S_{II}	r_S	0.017	0.455**	0.009	0.356*	0.419**	0.455**	–	−0.110
	p	0.917	0.003	0.954	0.022	0.006	0.003	–	0.495

*, **. Correlation is significant at the 0.05, 0.01 levels respectively (2-tailed).

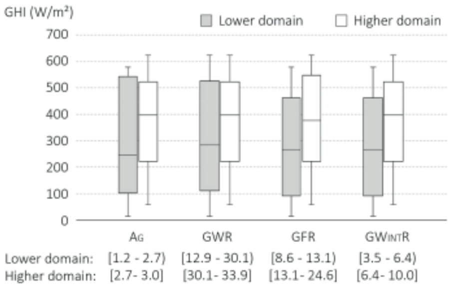


Fig. 7. Distribution of global horizontal irradiance GHI (W/m^2) for pairs of subgroups from S_{II}, each subgroup selected by dichotomizing S_{II} into two groups (Lower domain, Higher domain) based on the median value of each variable A_G, GWR, GFR and $GW_{INT}R$.

findings and a few counter-intuitive outcomes. Overall, the proven suitability of the utilized scales for measuring perceived brightness indicates that it can be a powerful tool for post-occupancy daylight evaluations in residential spaces. The same scales have previously been deployed to evaluate different working environments [10], to test effects of electric lighting installations in classrooms [11] and outdoor urban paths [12], and to evaluate the effect of season on electric lighting use by office workers [13]. With the present study, the usability of this instrument is extended and proven reliable i) for residential spaces, and ii) for daylight as the sole illuminant.

The reliability results presented here for the Distribution component indicate that such a dimension could not be satisfactorily captured using the corresponding three scales. This is to be expected, as in previous work, these scales have been shown to load on different factors, depending on the experimental set up or the lighting source. When used outdoors, the scale "*Unfocused – Focused*" has been shown to associate with Brightness under LED and discharge lamps [12], but has been shown to load on the Distribution component (grouped with scale "*Scattered – Concentrated*") when evaluated indoors under fluorescent and LED lighting [11]. In this study it loaded on both factors, and only correlated weakly with all other scales. This ambiguity in past studies and within the current work led to discarding this scale from further processing. Similarly in a counter-intuitive way, the "*Uneven distributed – Even distributed*" scale loaded higher on the Brightness component (0.667) than it did on the Distribution component (0.239). In previous studies, this scale has been shown to not correlate with any other scale [12] or to correlate more strongly with qualities such as flicker, sharpness, softness or pleasantness compared to qualities related to light distribution [11]. It can therefore be argued that the semantic meaning of these two scales (in Swedish) are in need of scrutiny in terms of their suitability for i) different light sources and ii) type of environment (indoors or outdoors).

The self-administered character of the questionnaire led to random sampling of participating apartments, and yielded specific sample characteristics. On the positive side, the satisfactory distribution of age among participants is a strong argument for the robustness of the exploratory factor analysis, since i) age is considered by far the most influential factor of visual capacity, and ii) the utilized scales pertain primarily to vision and not e.g. to mood state or social interaction. In addition, validation against irradiance measurements indicated that there was a strong correlation between GHI and Brightness, confirming content validity for the questionnaire scales pertaining to brightness. On the other hand, it was not possible to trace associations between Brightness and geometric attributes for the evaluated samples S_{225}, S_I and S_{II}, owing to the study design and its limitations. Any association between geometry and Brightness in the S_{II} rooms was eventually shown to be dictated by the confounding association between geometric attributes and GHI. In addition, there were between-geometric-attributes correlations, i.e. the glazing area A_G in sample S_I correlated strongly with the floor area A_{FLOOR} ($r_S = 0.691$, $p < 0.001$), a correlation stemming from intuitive architectural design and conventional wisdom. In other words, increasing the glazing size meant increasing the floor area for S_I rooms. In addition, architectural practice dictated by functionality led to balconied rooms (S_{II} rooms) having higher glazing areas relative to façade area or interior walls area, compared to rooms without balconies (S_I rooms). For the vast majority of cases, façades behind a balcony were found glazed throughout the balcony width, owing to additional fenestration consisting of glazed doors, used to access the balcony. This design effectively provides a broader view out, as well as a broader area of high luminance (glazing) relative to the rest of the vertical surfaces (walls). The effect of vertical surface luminance on perceived brightness was not covered in this study, neither was view out, but could be investigated in the future to ensure further validity for the utilized OBEA instrument.

However, the aim of the association study between Brightness and geometry in this paper was not to rule out certain attributes as insignificant, since this would require a full factorial design, which was not possible due to random sampling. The aim of the study was to identify the geometric attributes that are universally affecting perception of daylight, regardless of the values of the remainder room attributes. The same approach applies for the Mann-Whitney *U* test that evaluated the relevance of specific benchmark values to brightness perception. The investigated variables of VSC and GFR were manually dichotomized on specific benchmark values that relate to existing codes and recommendations (requirements: VSC $\geq$ 20 %, GFR $\geq$ 10 %). The aim of the study was to evaluate whether these benchmarks are universally applicable, i.e. that sufficient brightness can be perceived by conforming to these benchmarks alone, regardless of the remainder room attributes. The GFR $\geq$ 10 % criterion was proven to be robust in this case, while the VSC $\geq$ 20 % could not be identified as a clear limit between rooms perceived as dark or bright. Neither was any other VSC benchmark value. This may come as no surprise, as the inception of VSC was not founded on occupant-based subjective evaluations of spaces, but rather on vertical illuminance incident on fenestration [34], with which the indoor average daylight factor is associated.

5. Conclusions

This article focused on methodological aspects related to occupant-based evaluations of residential environments. The study was performed using a questionnaire survey in 75 apartments comprising 225 rooms in typical multi-family buildings. An observer-based environmental assessment instrument was evaluated for its suitability to measure perceived brightness and distribution, and its relation to room geometry was tested to highlight key geometric attributes. The main outcomes of this research can be summarized in the following points:

5.1. *Instrument suitability*

The utilized observer-based instrument was proven reliable and valid for its use in measuring perceived brightness levels in residential spaces. One factor "Brightness" comprising four bipolar scales was derived with a Cronbach's alpha equal to 0.89, indicating high internal reliability. Construct validity of this factor was confirmed by its strong association with global horizontal irradiance ($r_S = 0.566$, $p = 0.006$). Overall, it can be confirmed that the utilized Brightness scales are reliable and valid for measuring the intended quality. On the contrary, the Distribution scales described in this work were lacking internal reliability, and their factor loadings were found inadequate to capture perceived daylight distribution. The semantic meaning of these scales (in Swedish) are in need of close examination, if they are to be suitable for measuring daylight distribution in residential rooms.

5.2. *Key geometric attributes*

Of all geometric attributes tested, those pertaining to window size (A_G, GWR, GFR, $GW_{INT}R$) were found to correlate more strongly with perceived brightness, for rooms with a balcony obstruction above their fenestration (A_G: $r_S = 0.455$, $p < 0.005$, GFR: $r_S = 0.419$, $p < 0.01$, $GW_{INT}R$: $r_S = 0.455$, $p < 0.005$ and GWR: $r_S = 0.356$, $p < 0.05$). Further investigation revealed that the confounding effect of global horizontal irradiance was contributing to these associations. However, these geometric attributes pertain to the view out, as well as to the luminance distribution of vertical surfaces in the field of view, which were not examined in this study. Further investigation on these aspects is necessary to establish cause-and-effect relationships between geometry and brightness perception. In terms of established rules of thumb in building codes and literature, the typical GFR benchmark of 10 % was found to satisfactorily distinguish between rooms perceived as darker (GFR $\leq$ 10 %) and brighter (GFR $\geq$ 10 %). So was the GHI benchmark of 300 W/m^2 for the investigated timespan. On the contrary, the VSC $\geq$ 20 % benchmark could not be identified as a clear-cut limit between rooms perceived as brighter or darker.

Funding

This research was funded by the Swedish Energy Agency (Energimyndigheten, grant nr 41816-2), Arkus (Stiftelsen Arkus) and ARQ (c/o White Architects AB, grant nr 12:2016).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are indebted to all residents who took part in this study, their opinions on daylight were crucial to our research. We also thank the housing companies (MKB, HSB, Stena Fastigheter and Riksbyggen) for contacting their tenants in order to acquire permission for this work. We thank Henrik Davidsson for calibrating the pyranometer used for the global horizontal irradiance measurements, and Niko Gentile for support with the data logger. We are also very grateful to Olof Wiese from Utskottet for providing the precious space and mounting equipment to install the pyranometer. Danai Vogiatzi is acknowledged for monitoring and extracting irradiance data at the necessary time intervals. We also thank Andreas Eggertsen Teder for support in contacting the different housing companies and managing meetings. Magnus Fischer and Jouri Kanters are acknowledged for their fruitful comments during the pilot study that shaped the questionnaire layout, and finally, special thanks to Marwan Abugabbara for undertaking the Arabic translation of the questionnaire and to Ludvig Haav for undertaking the Swedish translation.

References

[1] M.-C. Dubois, N. Gentile, C.N.D. Amorim, W. Osterhaus, S. Stoffer, R. Jakobiak, D. Geisler-Moroder, B. Matusiak, F.M. Onarheim, E. Tetri, Performance evaluation of lighting and daylighting retrofits: results from IEA SHC task 50, Energy Procedia 91 (2016) 926–937.

[2] C.-E.C.f. Standardization, European Standard EN 17037:2018 Daylight in Buildings, 2018.

[3] IES-LM-83-12, Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), Illuminating Engineering Society, New York, US, 2012, p. 14.

[4] M.B.C. Aries, M.P.J. Aarts, J. van Hoof, Daylight and health: a review of the evidence and consequences for the built environment, Light. Res. Technol. 47 (1) (2015) 6–27.

[5] J.A. Veitch, G.R. Newsham, O. National Research Council of Canada, Determinants of Lighting Quality II: Research and Recommendations, 1996.

[6] J.A. Veitch, Psychological Processes Influencing Lighting Quality, 2001, pp. 124–+.

[7] J.E. Flynn, A study of subjective responses to low Energy and nonuniform lighting systems, Light. Des. Appl. 7 (2) (1977) 6–15.

[8] D.K. Tifler, M.S. Rea, Semantic differential scaling: prospects in lighting research, Light. Res. Technol. 24 (1) (1992) 43–51.

[9] R. Küller, L. Wetterberg, Melatonin, cortisol, EEG, ECG and subjective comfort in healthy humans: impact of two fluorescent lamp types at two light intensities, Light. Res. Technol. 25 (2) (1993) 71.

[10] R. Kuller, L. Wetterberg, The subterranean work environment: impact on well-being and health, Environ. Int. 22 (1) (1996) 33.

[11] N. Gentile, T. Goven, T. Laike, K. Sjoberg, A field study of fluorescent and LED classroom lighting, Light. Res. Technol. 50 (4) (2016) 631–650.

[12] M. Johansson, E. Pedersen, P. Maleetipwan-Mattsson, L. Kuhn, T. Laike, Perceived outdoor lighting quality (POLQ): a lighting assessment tool, J. Environ. Psychol. 39 (2014) 14–21.

[13] P. Maleetipwan-Mattsson, Evaluation of lighting control systems. A case of occupants' experience and use of different control systems in office environments, in: Environmental Psychology Monograph No 21. Lund, Sweden, Department of Architecture and the Built Environment, Faculty of Engineering, Lund University., 2012.

[14] SCB, Statistics Sweden - Dwelling Stock 31/12/2017, 2018.

[15] T. Hall, Stockholm: the Making of a Metropolis, Routledge, London, 2009.

[16] J. Rådberg, A. Friberg, Svenska Stadstyper : Historik, Exempel, Klassificering, Stockholm : KTH högskoletr., Stockholm, 1996, 1996.

[17] Boverket, Boverket's building regulations - mandatory provisions and general recommendations, BFS 2011:6 with amendments up to BFS 2018 4, 2018.

[18] Malmö Stad, Stadsbyggnadskontorets arkiv. https://malmo.se/Service/Bygga-och-bo/Stadsbyggnadskontorets-arkiv.html, 2019.

[19] Lantmäteriet, Swedish Surveying and Cadastral Agency, 2018.

[20] ESRI, ArcGIS ArcMap, 2016.

[21] Lantmäteriet - Laserdata Skog. https://www.lantmateriet.se/sv/Kartor-och-geografisk-information/geodataprodukter/laserdata-skog/?steg=1, 2019.

[22] Grasshopper, Algorithmic Modelling for Rhino, Robet Mcneel and associates, 2018.

[23] I. Bournas, M.-C. Dubois, Daylight regulation compliance of existing multi-family apartment blocks in Sweden, Build. Environ. 150 (2019) 254–265.

[24] P.J. Littlefair, Site layout planning for daylighting and sunlighting A guide to good practice, Build. Res. Establishment, Watford 85 (1991).

[25] W.L. Greg, S. Rob, Rendering with Radiance: the Art and Science of Lighting Visualization, Morgan Kaufmann Publishers Inc, 1998.

[26] M. Sadeghipour Roudsari, M. Pak, Ladybug: a parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design. Proceedings of the 13th International IBPSA Conference Held in Lyon, France, 2013, pp. 3128–3135.

[27] SCB, Statistics Sweden - Swedish and Foreign-Born Population by Region, Age and Sex, 2018, 2000 - 2018.

[28] P.R. Boyce, Human Factors in Lighting, 2. ed. ed., Taylor & Francis2003.

[29] N. Gentile, M.-C. Dubois, W. Osterhaus, S. Stoffer, C.N.D. Amorim, D. Geisler-Moroder, R. Jakobiak, A toolbox to evaluate non-residential lighting and daylighting retrofit in practice, Energy Build. 123 (2016) 151–161.

[30] Greater London Authority, Representation Hearing Report D&P/3067/03 - Appedix 1, Daylight and Sunlight Assessment Tests, 2013.

[31] SIS, Standardiseringskommissionen i sverige - SVENSK Standard SS 91 42 01, 1988.
[32] S. Kunkel, E. Kontonasiou, A. Arcipowska, F. Mariottini, B. Atanasiou, Indoor Air Quality, Thermal Comfort and Daylight - Analysis of Residential Building Regulations in Eight EU Member States, 2015, p. 100.
[33] H.F. Kaiser, J. Rice, Little Jiffy, Mark iv, Educ. Psychol. Meas. 34 (1) (1974) 111–117.
[34] P. Littlefair, Daylight, sunlight and solar gain in the urban environment, Sol. Energy 70 (3) (2001) 177–185.

Paper 5

Building and Environment 180 (2020) 106977

Contents lists available at ScienceDirect

Building and Environment

journal homepage: http://www.elsevier.com/locate/buildenv

Residential electric lighting use during daytime: A field study in Swedish multi-dwelling buildings

Iason Bournas [*], Marie-Claude Dubois

Energy and Building Design, Department of Architecture and the Built Environment, Lund University, Box 118, SE, 221 00, Lund, Sweden

ARTICLE INFO

Keywords:
Electric lighting use
Survey
Residential
Room function
Orientation

ABSTRACT

This paper evaluates the effect of room function and orientation on daytime electric lighting use in dwellings, and the confounding role of room design aspects. A questionnaire survey was conducted in six multi-dwelling buildings including 75 apartments located in Malmö, Sweden (Latitude: 55.6 °N). Occupants were asked how often they use electric lighting during daylight hours, in three rooms of different functions, namely the kitchen, the living room and the bedroom. In a preliminary step, the behavior of occupants regarding electric lighting use was evaluated, to test whether design and orientation can affect switch-on behavior or whether it is random and unpredictable. In the next step, statistical analysis was performed to verify whether there is a relation between daytime electric lighting and room function, room orientation or both. Results indicate that electric lighting use did not vary significantly among occupants living in rooms of similar geometry, especially when living in West-oriented rooms. With respect to room function, overall it was shown that daytime electric lighting use was more frequent in kitchens. However, the study showed that electric lighting use in kitchens is associated with specific design features and not with room function per se. With respect to orientation, a consistent finding was that West-facing rooms use electric lighting less frequently compared to rooms of other orientations, and significantly less frequently compared to East-facing rooms, which can be explained by diurnal occupancy patterns characterizing residential spaces. The implications of the findings on daylight design criteria for residences are discussed.

1. Introduction

The profound effect of daylight on occupant health and well-being has been documented in international literature [1–5], hence its provision within indoor spaces is stipulated via building codes [6], international standards [7,8] and certification schemes [9,10]. In addition, considerations of energy use [11] as well as occupants' preference for daylighting over electric lighting [12,13] imply that electric lighting should be kept to a minimum during daytime. However, the value of electric lighting is not to be underestimated, as i) it is a necessary complement to daylight for time periods when the latter is insufficient for performing visual tasks and ii) it is necessary when daylight distribution across a given space is not satisfactory. These two reasons can explain why electric lighting may be used even during daytime. The former one indicates that the frequency of electric lighting use is a function of indoor daylight availability, hence related to factors such as room geometry, fenestration, orientation, surroundings, latitude, etc. The latter point suggests that it is also dependent on subjective judgements of the luminous environment and individual preferences for space character. To reduce the frequency it is used, one cannot dictate subjective views, but can define sound design choices that have an implicit effect on indoor daylight availability. The purpose of this paper is to highlight those factors affecting electric lighting use in residential spaces, to inspire good design practice.

Meanwhile, it is an observed trend that urban areas in Sweden as well as internationally are experiencing densification, caused by population increase and people's decisions to settle in urban rather than rural environments. Densification in urban areas has recently been shown to reduce daylight access in Swedish dwellings [14]. In addition, research on human activity patterns in the western world has shown that people tend to spend approximately 90% of their time indoors, where by far the largest portion of time is spent in residences (nearly 70% of time) [15]. It is thus necessary to identify factors affecting electric lighting use in urban areas, particularly in residential spaces, to limit national and global electricity use. In addition, it is important to evaluate the frequency of electric lighting use during daytime, to assess whether

---

[*] Corresponding author.
E-mail address: iason.bournas@ebd.lth.se (I. Bournas).

https://doi.org/10.1016/j.buildenv.2020.106977
Received 15 January 2020; Received in revised form 13 May 2020; Accepted 13 May 2020
Available online 28 May 2020

daylight design can indeed affect electric lighting use. To answer these questions, the present paper investigates the effect of room function and room orientation on daytime electric lighting use in apartment spaces. At the same time as these two factors are analyzed, room geometry is taken into account, to evaluate the extent of its significance in dictating electric lighting use.

1.1. Objective

The main goal of this study was to evaluate whether room function and room orientation have an impact on daytime electric lighting use in residential spaces. This knowledge can be proven useful for the inception of future design criteria for dwellings, for instance guidelines on beneficial orientations for specific rooms or different daylight criteria for different rooms. Regarding function, it was hypothesized that room function per se does not affect the frequency of electric lighting use during daytime. Instead, it was expected that electric lighting use would depend on geometric features of rooms, owing to the daylight potential dictated by room geometry. Regarding orientation, it was hypothesized that daytime electric lighting use would be significantly different between rooms of different façade orientations. The hypothesis was founded on the fact that it is more likely for residential spaces to be occupied from the afternoon hours onwards rather than during morning hours or in noon, as has been shown in previous studies in Sweden [16–19], which means that the sun position i.e. the daylight potential during occupancy favors some orientations over others.

A secondary goal of this study was to evaluate the extent of occupant behavior diversity it terms of electric lighting use. It was hypothesized that although different occupants may use electric lighting differently, as it may be dictated by culture, environmental awareness or individual preferences, the diversity can be reduced when occupants live in similar rooms in terms of geometry, function and orientation. Knowledge on this aspect can help prove that design indeed dictates human behavior to a certain extent, and that electric lighting use in dwellings is not completely random or unpredictable due to occupant habits and preferences.

2. Method

2.1. Sampled buildings

The survey was carried out in six residential building developments located in the central and metropolitan region of Malmö (Latitude: 55,6°N), Sweden. They were selected to include only multi-dwelling buildings, which is the most common type of residence in Sweden (51%) [20], and consistently the most common housing type constructed annually since 1985 [21]. An architectural criterion for the selection of these particular buildings was their block typology, more specifically its relation to typical urban blocks identified in Swedish planning history [22,23]. The aim for the selection was to evaluate electric lighting use within a sample of typical Swedish residential buildings. Fig. 1 shows aerial views of the surveyed developments, along with the number of evaluated rooms and typical floor plans per typology. Overall, the study included 75 apartments comprising 225 rooms (sample S_{225}, N = 225), and evaluated only kitchen rooms (K), living rooms (L) and bedrooms (B). The room samples per typology are shown in Fig. 1 (S_{LT}: N = 36, S_{HT}: N = 69, S_{LC}: N = 51, S_{SC}: N = 12, S_{HE}: N = 36 and S_{EC}: N = 21).

2.2. Room geometries and surrounding obstructions

For a better comprehension of the evaluated rooms, Table 1 includes means (M) and standard deviations (SD) of attributes pertaining to surrounding obstructions and geometry per room function and building typology. Surrounding obstructions were quantified by calculating the Vertical Sky Component (VSC) according to Littlefair [24]. Details on the VSC calculation procedure can be found in Ref. [25]. The geometric attributes presented in Table 1 include the glazing area (A_G), the floor area (A_{FLOOR}), the glass-to-wall ratio (GWR), the glass-to-floor ratio (GFR), the glass-to-interior-surfaces-area ratio ($GW_{INT}R$), which is the glazing area relative to the sum of interior wall areas and the room depth (D). The values in bold correspond to attributes where the standard deviation (SD) was less than 10% of the mean (M), indicating cases where there is homogeneity among rooms of the same function (K or L or B) within a given building typology. For instance, the most homogenous surrounding obstructions (VSC) can be observed for B in Low-rise towers, for K and L in High-rise elongated and for L in Exterior circulation. The latter two typologies have homogenous rooms with respect to most geometric attributes, indicating that their plan layouts are "typical", i.e. repeated modules of rooms can be found throughout the overall plan and across different floors. Geometry is also nearly identical among K in Low-rise towers and High-rise Towers. Comparing geometric attributes between different functions (K vs L, K vs B, L vs B), they were found to be similar in specific typologies. The term "Similarity" in Table 1 refers to similar mean values (M) of geometric attributes between two room functions. This is the case in i) Low-rise towers (K ≈ B),

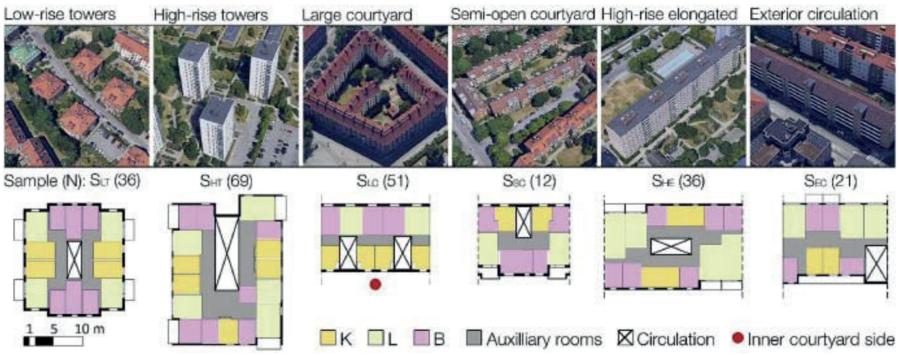


Fig. 1. Aerial view of developments, typical floor plans and room samples per typology. Aerial images © Landsat/Copernicus and Data S O, NOAA, U.S. Navy, NGA, GEBCO.

Table 1
Statistical data of the evaluated rooms, including mean (M) and standard deviation (SD) for each geometric attribute and VSC, calculated per room function K, L, B and building typology.

		Low-rise towers			High-rise towers			Large courtyard			Semi-open courtyard			High-rise elongated			Exterior circulation		
		K	L	B	K	L	B	K	L	B	K	L	B	K	L	B	K	L	B
VSC (%)	M	27.1	18.2	30.9	33.4	26.4	15.5	24.4	29.8	30.9	26.6	5.3	22.6	37.1	13.4	36.4	9.8	28.8	9.9
	SD	5.6	4.5	2.9	4.9	10.9	14.3	4.7	5.0	4.0	12.0	1.8	10.0	1.9	0.4	4.3	2.9	2.5	2.0
A_G (m^2)	M	1.1	3.8	1.1	1.2	3.7	1.8	1.2	1.7	1.7	1.2	1.9	1.1	1.1	2.7	1.1	1.2	3.1	2.5
	SD	0.1	0.6	0.2	0.1	0.6	1.1	0.0	0.4	0.4	0.3	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0
A_{FLOOR} (m^2)	M	11.7	18.5	12.7	14.3	20.7	10.8	11.3	18.1	15.5	12.7	19.6	10.4	10.5	22.7	11.1	12.0	21.6	11.7
	SD	0.8	0.8	2.3	0.4	2.2	2.6	2.3	2.0	3.1	1.7	0.2	0.9	0.0	3.2	0.9	0.0	0.0	0.0
GWR (%)	M	14.3	15.7	12.8	15.4	25.2	20.2	16.6	14.9	14.3	12.3	17.3	15.1	13.6	30.4	13.6	15.9	30.3	33.9
	SD	0.9	2.3	1.7	0.6	9.1	11.0	5.8	2.8	1.8	2.6	4.6	4.8	0.0	0.8	0.0	0.0	0.0	0.0
GFR (%)	M	9.8	20.6	8.8	8.8	17.6	14.6	11.3	9.8	11.3	9.0	9.8	10.8	10.9	12.0	10.4	9.8	14.6	21.5
	SD	0.3	2.2	2.4	0.6	2.0	8.9	2.0	3.0	3.1	1.0	0.2	3.2	0.0	1.6	0.8	0.0	0.0	0.0
$GW_{INT}R$ (%)	M	3.1	10.0	3.0	3.4	9.2	5.8	3.5	4.0	4.2	3.2	4.7	3.6	3.7	6.0	3.6	3.5	7.4	8.1
	SD	0.3	1.5	0.7	0.2	1.3	3.8	0.4	1.1	1.1	0.5	0.2	0.9	0.0	0.5	0.1	0.0	0.0	0.0
D (m)	M	4.8	4.6	4.8	4.7	4.5	3.4	4.0	4.7	4.2	4.2	4.8	3.8	3.4	6.3	3.6	4.4	5.5	4.3
	SD	0.2	0.8	0.8	0.2	0.4	0.8	0.5	0.4	0.7	0.4	0.8	0.2	0.0	0.9	0.3	0.0	0.0	0.0
Similarity:		K ≈ B			none			L ≈ B			none			K ≈ B			none		

ii) Large-courtyard (L ≈ B) and iii) High-rise elongated (K ≈ B). There were no similarities between K and L in any building typology, i.e. the kitchen was always designed significantly different compared to the living room. During the study, geometrical homogeneity between rooms was found to decrease electric lighting use differences between different functions and occupants.

2.3. Survey subjects and questionnaire

Participants were contacted via mail sent to their civic addresses. The majority of questionnaires (90%) were filled in within a week from spring equinox, in 2018. The questionnaire was distributed in three languages (Swedish, English and Arabic), with the intent to increase the response rate. However, the Swedish version was used by all respondents, indicating a Swedish background among them. The response rate was calculated to 13% after excluding i) incomplete questionnaires, ii) questionnaires that were returned by the post service due to address changes and iii) questionnaires that corresponded to smaller apartments not including all three room functions K, L and B. The final number of questionnaires that were processed was 75, corresponding to 225 rooms (3 x 75). Post-processing confirmed that there was satisfactory variation in age and gender among participants. Details on these demographics can be found elsewhere [25].

Responses on electric lighting use were given on a seven-point Likert scale for each room function. The scale consisted of two bipolar adjectives (*never – always*). Fig. 2 shows the scale corresponding to the kitchen room. To avoid confusion of the term "daytime" with a working schedule (e.g. 8:00–17:00), the underlined clause in Fig. 2 was used instead, defining the considered timespan as the period "when the sun is above the horizon". In this way, seasonal changes in daylight availability can be considered, effectively prompting participants to report electric lighting use outside night-hours. The frequency of electric lighting use was quantified for each room function with an index ranging from 1 = never to 7 = always.

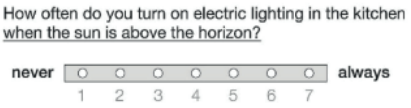


Fig. 2. The rating scale measuring frequency of daytime electric lighting use in the kitchen.

2.4. Preliminary study – effect of geometry, function and orientation on occupant behavior diversity

A preliminary study was conducted to assess the extent to which electric lighting use is dependent on individual occupant behavior. Cultural practices in different countries, environmental awareness and individual preferences are known factors that can affect behavior in terms of lighting use [26,27]. Age, apart from affecting visual capacity [28] has also been shown to affect hourly electric lighting use patterns in Swedish apartments, especially during weekends [29]. This diversity notwithstanding, it was expected that different occupants would report similar electric lighting use if living in similar rooms. For this purpose, 24 subsamples of S_{ALL} were extracted, each subsample containing geometrically identical rooms of a specific function (K or L or B), a specific orientation (North or East or South or West), and nearly identical in terms of surroundings. By "nearly identical", it is meant that the VSC of rooms in each subsample did not deviate more than 3.3% from the mean VSC in the subsample, which is a negligible deviation. The apartment plans (a - g) that include these rooms are shown in Fig. 3. For instance, from the Large-courtyard typology (plan e), the rooms extracted were five identical South-facing kitchens, five identical North-facing living rooms and five identical North-facing bedrooms. The rationale of categorizing rooms as facing North, East, South and West is described under section *2.5.2*. For each of the individual rooms shown in Fig. 3, the diversity between occupants was assessed by calculating the median absolute deviation (MAD) of responses in each subsample, a higher MAD indicating higher deviation between occupants in the particular subsample. The MAD is defined as the median of the absolute deviations of responses from the median response in the sample. It is a robust measure of data dispersion when there are outliers in the data distributions [30], which was the case in this study.

2.5. Evaluated factors of daytime electric lighting use and analysis steps

Two factors were evaluated for their effect on daytime electric lighting use: i) room function and ii) room orientation. Each factor was analyzed following three consecutive steps (Step 1, Step 2 and Step 3),

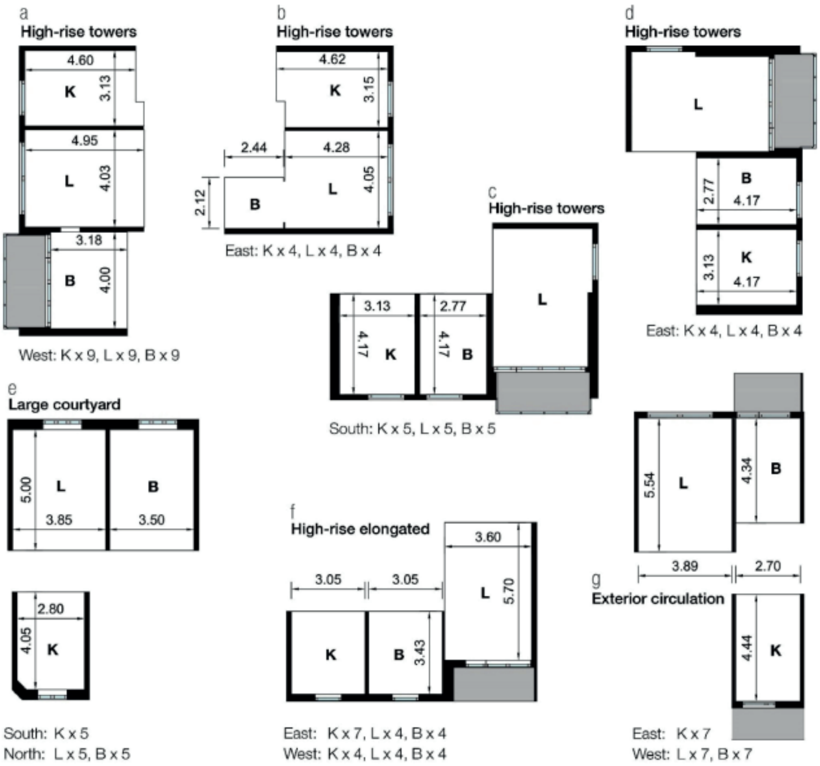


Fig. 3. Plans of rooms (a–g) with overall dimensions [m] for the assessment of occupant behavior diversity in terms of daytime lighting use. Indicated below the plans is the number and orientation of identical rooms per function K, L, B.

narrowing samples and increasing room homogeneity in each step, as shown schematically in Fig. 4. By comparing results between steps, the confounding role of room geometry could be observed. For a factor affecting electric lighting use consistently in all three steps (factor effective for diverse rooms and for identical rooms), its effect could be considered strong regardless of room geometry.

In Step 1, the effect of each factor was assessed considering the overall room sample (S_{225}). This step was followed in order to identify (if

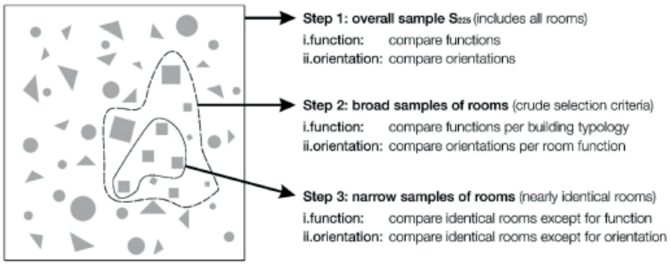


Fig. 4. Schematic sample extraction, with the type of comparisons performed per factor (i. room function and ii. room orientation) in each analysis step.

Table 2
Summary of extracted samples and statistical tests performed per factor in each analysis step.

Factor	Step	Sample	Test
i. Room function	1	3 samples (S_K, S_L, S_B, N = 75 each), each containing rooms of the same function.	Friedman Wilcoxon Signed-Ranks
	2	6 samples (S_{LT}, S_{HT}, S_{LC}, S_{SC}, S_{HE}, S_{EC}, N = 36, 69, 51, 12, 36, 21 respectively), one per building typology (see Fig. 1).	% apartments $\Delta > 2$ % apartments K > L % apartments K > B
	3	1 sample (S_{46}, N = 46) including 23 pairs of nearly-identical rooms in all aspects apart from room function (see Fig. 5).	Wilcoxon Signed-Ranks
		2 samples (S_{KB}, N = 34, S_{LB}, N = 12), subsamples of S46, the one including similar K and B, and the other including similar L and B (see Fig. 5).	$\Delta > 2$ for K vs B and L vs B
ii. Room orientation	1	4 samples (S_N, S_W, S_S, S_E, N = 35, 85, 38, 67respectively), according to orientation	Response distributions and % responses > 4
	2	4 samples ($S_{N\_VSC\_GFR}$, $S_{W\_VSC\_GFR}$, $S_{S\_VSC\_GFR}$, $S_{E\_VSC\_GFR}$, N = 10, 46, 22, 38 respectively) according to orientation, only including rooms with GFR ≥ 10% and VSC ≥ 15%.	Mann-Whitney *U* test
	3	10 samples grouped in 5 pairs, with rooms in each pair being identical in all aspects apart from orientation (see Fig. 7).	Response distributions

any) general pattern encompassing all investigated rooms. In Step 2, a crude selection criterion was used to select rooms e.g. to assess room function in Step 2, different building typologies were analyzed separately. Finally, in Step 3, the effect of the factor under assessment was evaluated after eliminating all confounding associations. This was achieved by extracting narrow samples consisting of rooms identical in all aspects apart from the analyzed factor. The extracted samples are presented in subsections *2.5.1 and 2.5.2*, which correspond to the two studied factors. Table 2 contains a summary of the samples and the statistical tests performed per step, to facilitate reading. Each test was chosen according to the methods prescribed for analyses applicable to empirical research in behavioral science [31]. For all tests, results were considered statistically significant when $p < 0.05$.

2.5.1. *Room function*

Room function was considered as it has previously been shown to affect the lighting load [W] of rooms in Sweden [29], as well as the number and type of lamps used to illuminate them [32]. In addition, a recent study in Denmark indicated that rooms of different functions (K, L, B) are occupied during different, identifiable time-periods of the day [33], which can have a direct effect on indoor daylight availability per function. To assess the actual effect of room function, occupant responses were evaluated following three steps, progressing analyses gradually from the overall room sample to narrow samples of identically designed rooms. In all steps, analysis was conducted within subjects, to control for any diversity between occupants, as this was identified during the preliminary study.

2.5.1.1. Step 1. For Step 1, sample S_{225} was divided in three subsamples according to function (S_K, S_L, S_B, N = 75 each). This was done to test whether a specific function (K or L or B) uses daytime electric lighting more frequently, statistically across all evaluated apartments. A nonparametric Friedman test was performed to evaluate whether significant differences between subsamples S_K, S_L, S_B exist, followed by posthoc Wilcoxon Signed-Ranks Tests to identify differences between specific pairs of subsamples (S_K vs S_L, S_K vs S_B, S_L vs S_B). Both tests were appropriate here as they eliminate the variation due to occupant differences (e.g. behavior) and only assess the variation between room functions. The Friedman test is similar to a one-way ANOVA with repeated measures, but is more fit here as it analyzes variances based on ranks of scores, alleviating the issue of the violation of normality, which was the case for samples S_K, S_L and S_B. Similarly, the Wilcoxon Signed-Ranks Test is the non-parametric alternative to a paired-samples *t*-test.

2.5.1.2. Step 2. In Step 2, comparisons between functions were performed per building typology (samples S_{LT}, S_{HT}, S_{LC}, S_{SC}, S_{HE} and S_{EC}, Fig. 1). To evaluate the deviation between two functions, the absolute difference (Δ) between responses was calculated for each apartment ($|K - L|$, $|K - B|$, $|L - B|$). A higher percentage of apartments where Δ was greater than 2 points ($\Delta > 2$) was considered an indicator of high deviation between two functions in that typology. For typologies where low deviations were identified ($\Delta > 2$ in few apartments), the room characteristics shown in Table 1 were observed to assess the relationship of electric lighting use with geometric features. In addition, as Step 1 revealed that electric lighting use was more frequent for K compared to the other functions, it was tested whether electric lighting use in K was still higher when compared to L, B that were similarly designed (similar dimensions with K). For this purpose, the share of apartments where K > L and K > B was calculated and related to room geometric characteristics.

2.5.1.3. Step 3. To corroborate that electric lighting use is not affected by room function per se but rather by geometric features and orientation of rooms, only apartments including two nearly identically designed rooms were considered in Step 3. Effectively, this allowed for a comparison between two responses from the same occupant, one response per room function, with functions identically designed. For this purpose, a sample of 46 rooms was extracted (S_{46}, N = 46), consisting of 23 pairs of rooms in 23 apartments. In 17 apartments K was designed similarly to B (sample S_{KB}, N = 34), and in 6 apartments L was designed similarly to B (sample S_{LB}, N = 12). The plans of the rooms included in S_{KB} and S_{LB} are shown in Fig. 5, along with the number of pairs of nearly identical rooms (K, B and L, B) for each orientation. Initially, a Wilcoxon Signed-Ranks Test was performed on S_{46} to evaluate the difference in daytime electric lighting use between any two different functions, and subsequently absolute differences in responses ($\Delta > 2$) were calculated for S_{KB} and S_{LB} to evaluate differences between K, B and L, B separately.

2.5.2. *Room orientation*

The effect of room orientation was investigated as orientation is a fundamental strategy of daylight design, the south considered the "optimum" choice for annual daylight availability, e.g. for living rooms [34]. However, when considering occupancy patterns in residential spaces, it is probable that they are occupied in the afternoon hours as suggested by relevant literature [17,18]. This implies the superiority of the West orientation in terms of indoor daylight availability during occupancy, owing to the sun position in the afternoon. As with room function, the effect of orientation was evaluated in three consecutive steps, progressing from comparing diverse rooms to eventually comparing identical rooms.

2.5.2.1. Step 1. In Step 1, the overall room sample S_{225} was divided in four samples, S_N (N = 35), S_W (N = 85), S_S (N = 38) and S_E (N = 67), corresponding to North, West, South and East respectively. The

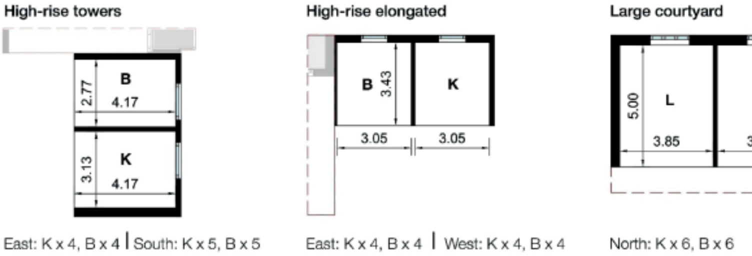


Fig. 5. Plans of nearly identical rooms of different functions (K, L, B) for assessing the effect of room function on daytime electric lighting use, sorted per building typology. Indicated below each plan is the number of rooms per function (K, L, B) and their orientation (North, East, South or West).

categorization was based on the angle between a room's façade normal and the cardinal direction due North, measured counter-clockwise starting from North as shown in Fig. 6. To categorize rooms, four distinct angular ranges were defined based on the mid-cardinal compass points, e.g. a room was considered West-facing for a façade normal direction between angles 45° and 135°, South-facing for a façade normal direction between angles 135° and 225° etc. For double-aspect window designs, the façade normal was set to the direction defined by the bisectrix of the individual window normal directions. Eventually, to compare samples S_N, S_W, S_S and S_E, the frequency of responses per sample was plotted and the percentage of responses exceeding 4 was calculated (responses equal to 5, 6 or 7), a higher percentage indicating more electric lighting use for a given orientation.

2.5.2.2. Step 2. In Step 2, analysis was conducted considering S_N, S_W, S_S and S_E, but including only rooms with GFR $\geq$10% and VSC $\geq$15% (samples: $S_{N\_VSC\_GFR}$, $N = 10$, $S_{W\_VSC\_GFR}$, $N = 46$, $S_{S\_VSC\_GFR}$, $N = 22$ and $S_{E\_VSC\_GFR}$, $N = 38$). This was done to evaluate differences between orientations considering rooms that exploit the daylight potential of each orientation. The GFR $\geq$10% i) is currently the daylighting benchmark in the Swedish building code [35], as well as in other national codes [6] and ii) has previously been shown to distinguish between rooms perceived as bright or dark under daylight by the same occupants [25]. In addition, rooms with a VSC below 15% are very difficult to be provided with daylight, unless very large windows are used [34]. Both VSC and GFR were similarly distributed among rooms in samples $S_{N\_VSC\_GFR}$, $S_{W\_VSC\_GFR}$, $S_{S\_VSC\_GFR}$ and $S_{E\_VSC\_GFR}$. The effect of orientation was assessed by performing one Mann-Whitney *U* test for each pair of orientations. Differences were considered significant for $p < 0.05$ and an effect size r [36] higher than 0.3, which is the medium effect size according to Ref. [37]. Additional tests were performed for each room function K, L, B separately, and significant differences were reported based on the test p value. The Mann-Whitney U statistic estimates the probability that a random response from one sample (e.g. a response for a West-facing room) exceeds a random response in a second one (e.g. a response for an East-facing room), irrespective of whether the two samples are similar in distribution shape. The test was appropriate here as the compared samples are independent, i.e. they come from responses of different participants. The U statistic is also robust to outliers, which were identified in $S_{W\_VSC\_GFR}$ (West orientation).

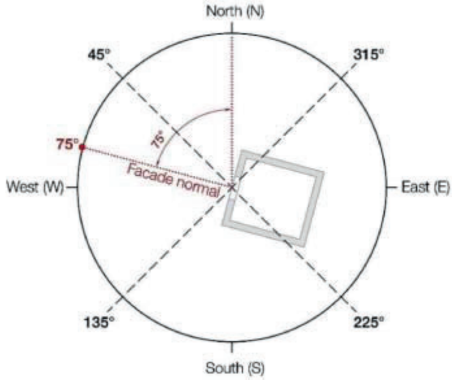


Fig. 6. Rationale for the categorization of rooms according to orientation (S_N, S_W, S_S and S_E). Example shown for a West-facing room.

2.5.2.3. Step 3. In Step 3, identical rooms oriented differently were compared. Their plans are shown in Fig. 7, for instance, in the High-rise towers eight East-facing kitchens were compared to seven identical West-facing kitchens. These rooms could only be retrieved from the typologies shown in Fig. 7, as only these buildings included rooms facing different directions while being of the same function and identically designed (Fig. 1, plans). Analysis was performed by means of descriptive statistics, comparing the median response in each sample.

3. Results

The following subsections *3.1*, *3.2* and *3.3* present results of the preliminary study, the study on room function and the study on room orientation respectively.

3.1. Results of preliminary study – diversity between occupants

Each boxplot in Fig. 8 corresponds to a sample of rooms of one function (K or L or B), one orientation (North or East or South or West), one geometry (plans a – g in Fig. 3), and nearly identical in surrounding obstructions. In other words, each boxplot represents a single room design, occupied by different occupants. Below each boxplot are the median response (Mdn) and the Median Absolute Deviation (MAD). A higher MAD indicates higher variation in daytime electric lighting use between occupants for a sample. If electric lighting use was identical among occupants living in similar rooms, all boxplots in Fig. 8 should look like the ones for L and B in High-rise towers (West), where responses do not spread across the rating scale, as they all have one value (in this case equal to 1), except for outliers (circular markers). Fig. 8 shows that there is a degree of diversity, which is different depending on sample. Two clear trends can be identified: i) West-facing rooms exhibit

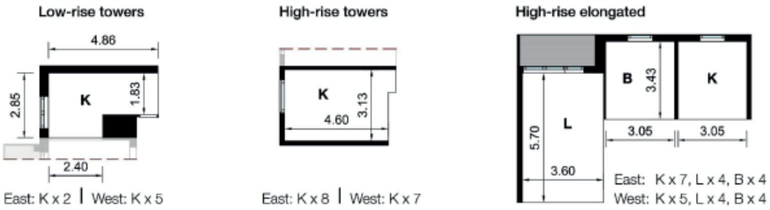


Fig. 7. Plans of rooms for assessing the effect of orientation on daytime electric lighting use, sorted per building typology. Indicated below the plans is the number of identical rooms per function (K, L, B) and orientation (East, West).

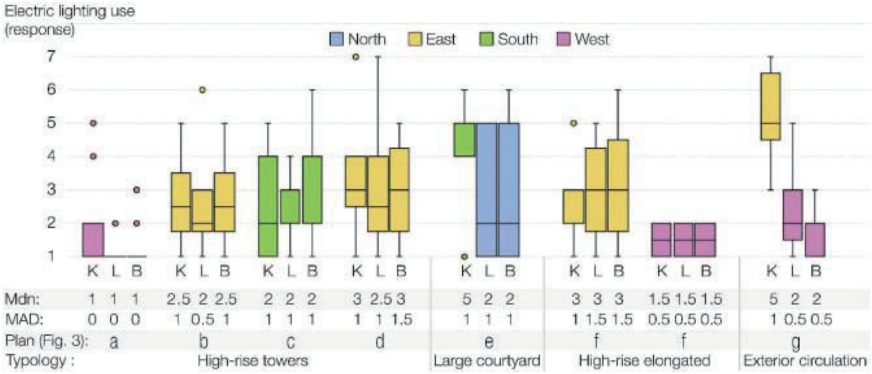


Fig. 8. Distribution of responses between 1 (never) and 7 (always). Each boxplot corresponds to one sample of nearly-identical rooms (see Fig. 3). Indicated below each boxplot are the median (Mdn) and the Median Absolute Deviation (MAD) per sample, along with the corresponding plan code (a-g, Fig. 3) and building typology.

less diversity and ii) responses in most samples are clustering either below or above the neutral point (response = 4). In terms of orientation, the MAD of responses are between 0 and 0.5 for West-facing rooms, equal to 1 for North-facing and South-facing rooms, and between 0.5 and 1.5 for East-facing rooms. This indicates that the least variation is found for West-facing rooms, which is true for all room functions. Observing the interquartile range of all samples, it is shown that responses lie mostly either below or above the neutral point (response = 4), i.e. responses are clustered either close to "never" or close to "always" for at least 75% of the occupants in each sample. For the majority of samples, responses lie on the lower range of the rating scale. However, the fact that design can lead to agreement is also true for occupants that use lighting more frequently. This is shown by the K responses in the Exterior circulation typology. These responses are clearly clustering to the higher end of the rating scale, and correspond to kitchens that are East-facing, have a balcony obstruction (plan g, Fig. 3), low VSC (9.8%, lowest among all typologies) and low GFR (9.8%) according to Table 1. There were two cases where response distributions clearly crossed the neutral point 4: L and B in the Large-courtyard typology. Investigating these samples further revealed that there were two occupants diverging from the rest, using significantly more lighting in both the living room and bedroom. The rest of the occupants gave low responses for both these rooms (response value 1 or 2). Finally, diversity was not shown to depend on room function per se, i.e. agreement between occupants was not dependent on the type of room.

3.2. Effect of room function on daytime electric lighting use

The effect of room function on daytime electric lighting use was evaluated within occupants, to eliminate effects of occupant behavior diversity, which were found to exist to a certain degree as per the previous subsection. Results are presented per analysis step.

3.2.1. Step 1 – Effect of room function considering the overall room sample

Step 1 considered all rooms in sample S_{225}, which was divided into three subsamples (S_K, S_L, S_B, N = 75 each) according to room function. The non-parametric Friedman Test of differences in responses between K, L and B rendered a Chi-square value of 15, which was significant ($p < 0.001$). In other words, the difference in daytime electric lighting use was found to differ significantly between rooms of different functions when including all 75 apartments. Wilcoxon tests were used to follow up this finding. It appeared that daytime electric lighting use was significantly different between K and L ($Z = -3.689$, $p < 0.001$) and between K and B ($Z = -2.913$, $p = 0.004$). No significant difference was found between L and B ($Z = -0.944$, $p = 0.345$). This indicates that for the overall room sample, occupants reported a significantly different daytime electric lighting use in their kitchens, compared to the rest of the rooms. In particular, lighting use was found to be significantly more frequent in kitchens. This finding is relevant to a recent room-level occupancy study in Denmark, where the kitchen room was shown to be occupied (on average) from afternoon hours onwards [33], when it is still daytime for a considerable amount of the year. The same study stated that the living room occupancy probability peaks at 21:00, when it is night, and the bedroom is only occupied in late hours for sleeping. In addition, the Swedish Time-Use Survey, which provided information on how people spend their time on various activities, showed that the most common household work is cooking and cleaning, and that the majority (both for men and women) do household work immediately after returning from work, the percentage of people doing household work peaking at approximately 17:30 [16]. Electric lighting, if necessary during daytime, will thus most probably be used in the kitchen.

3.2.2. Step 2 – Effect of room function in each building typology

Step 2 was followed to identify (if any) confounding associations between electric lighting use and room geometry and orientation. The association between pairs of functions in each apartment is shown in Fig. 9, where the size of the circular markers indicates the number of apartments for a given point on the scatterplot. The scatterplots are categorized from left to right according to pair of room functions (K vs L, K vs B, L vs B) and from top to bottom based on building typology. Descriptive statistics are shown below each typology thumbnail, including number of rooms (N) and median responses per function K, L, B (Mdn_K, Mdn_L, Mdn_B). Above each scatterplot, the percentage of apartments where $\Delta > 2$ is shown. Additionally for the K vs L and K vs B scatterplots, the percentage of apartments where the response for K was higher than the response for L and B ($K > L$, $K > B$) is shown. The most similar responses between functions ($\Delta > 2$ in fewer apartments) were reported in:

i) High-rise Towers, for K vs L, K vs B and L vs B ($\Delta > 2$: 13% for all three pairs of functions),
ii) Large courtyard, for L vs B ($\Delta > 2$: 6%)
iii) High-rise elongated, for K vs L, K vs B and L vs B ($\Delta > 2$: 8%, 0% and 8% respectively).
iv) Exterior circulation, for L vs B ($\Delta > 2$: 0%).

The results exhibit patterns that can be explained by the design similarities of rooms shown in Table 1 and Fig. 3. These similarities include the following: For High-rise towers, each of the 23 participating apartments had K, L, B oriented towards the same direction (Fig. 3, plans a, b, c, d), facing very similar surrounding obstructions (Fig. 1, aerial view). In addition, K and B were geometrically similar in 9 out of 23 apartments (39%), as shown in plans c and d of Fig. 3. For the Large-courtyard typology, in 13 out of 17 apartments (77%), L and B had the same orientation and surrounding obstructions. Moreover, L and B were very similar overall (Table 1, $L \approx B$), and nearly identical in 6 out of 17 apartments (35%) as shown in plan e of Fig. 3. With respect to the High-rise elongated typology, in 8 out of 12 apartments (67%), K, L, B had identical orientation and surrounding obstructions. In addition, K and B were very similar overall (Table 1), and in 8 out of 12 apartments (67%) they were identical (plan f in Fig. 3). Finally, for the Exterior circulation typology, in 7 out of 7 apartments both L and B were facing West with similar surrounding obstructions (Table 1, VSC values), while K was facing East (plan g in Fig. 3). The consistently identical orientation of L and B, which differed from K, led to low differences between L and B ($\Delta > 2$ in no apartment), and high differences between them and K. Interestingly, the association K vs L was significant in the Large courtyard typology ($r_S = 0.719$, $p < 0.01$), although $\Delta > 2$ was true for a significant percentage of apartments (29%). It can be observed in Fig. 9 that K responses were consistently higher than L responses in this typology. K had consistently the lowest glazing area A_G (Table 1: mean $A_G = 1.2$, SD = 0), and was always set facing the inner side of the courtyard (Fig. 1, plan), while L was always facing the street (K vs L, $r_S = 0.719$ but K responses ≠ L responses).

Overall, observing the circular markers that fall above the diagonal line (indicating $x = y$) in the K vs L and K vs B scatterplots, it is true that in most cases, K responses are higher than they are for the rest of the rooms, as previously revealed in Step 1. However, observing the percentage of apartments where $K > L$ and $K > B$, it is evident that the deviation between room functions is reduced when there is geometric similarity between rooms and depending on whether they share the same orientation or not, as elaborated in the previous paragraph. This indicates that design has the potential to decrease electric lighting use in kitchens.

3.2.3. Step 3 – Comparison of identical rooms differing in function

To corroborate that function per se is not the cause of increased daytime electric lighting use, Step 3 was followed. This included the comparison of rooms within 23 pairs (sample S_{46}), each pair consisting of nearly identical rooms, except for function (Fig. 5). In contrast to the results found in Step 1, the Wilcoxon Signed-Ranks Test indicated that daytime electric lighting use was not significantly different between different functions ($Z = -0.79$, $p = 0.430$). This implies that previous deviations found between K and L and between K and B are indeed a result of confounding geometric factors rather than the effect of the kitchen function per se. This finding can be supported by the data presented in Table 1, where kitchen rooms are shown to have the lowest GFR among functions across all typologies, nearly equal to 10% and in many cases lower, and not diverging from this value significantly (Table 1 GFR ≈ 10% and SD consistently very low for K in all building typologies).

Fig. 10 compares B vs K (sample S_{KB}, left diagram) and B vs L (sample S_{LB}, right diagram) separately, where S_{KB} and S_{LB} are subsamples of S_{46}. The labels on the grey markers indicate the number of apartments with identical pair values. It can be observed that the association between B and K responses is very strong ($r_S = 0.898$, $p < 0.001$), and that responses deviate more than 2 points ($\Delta > 2$) in only one pair of rooms ($B = 4$, $K = 7$). The association between B and L responses is strong ($r_S = 0.721$) but only tending towards significance ($p = 0.106$) owing to the low number of pairs ($N = 6$). However, both diagrams clearly show that there is no significant difference in daytime electric lighting use between room functions, when comparing nearly identical rooms. In addition, the fact that the analyzed 46 rooms in Fig. 10 include all four orientations (Fig. 5) is an indicator of the robustness of the finding. Overall, this section demonstrated that kitchen rooms statistically use more daytime electric lighting (Step 1), but room function is not the unique cause of this; lighting use can be affected by design (Steps 2 & 3).

3.3. Effect of room orientation on daytime electric lighting use

Following the same logic as with room function, the effect of orientation was evaluated in three consecutive steps, increasing room homogeneity gradually.

3.3.1. Step 1 – Effect of orientation considering the overall room sample

The percentage histograms in Fig. 11 show the distribution of responses on daytime electric lighting use for rooms in samples S_N, S_W, S_S and S_E. Responses that are higher than 4 correspond to answers closer to "always" (more frequent lighting use). The lowest percentage of high responses (>4) was given for West-facing rooms (14%), followed by South-facing (21%), North-facing (29%) and East-facing (29%) rooms. North and West distributions are more skewed, and include a high amount of low responses (<4, West: 83%, North: 71%), with the North distribution showing two clusters, one for low and one for high responses. Post-processing revealed that responses among different orientations did not correspond to equal shares of room functions, neither to equal shares of different fenestration sizes. To account for this, and to evaluate whether the differences between orientations are statistically significant, Step 2 was followed.

3.3.2. Step 2 – Effect of orientation considering rooms with VSC ≥15% & GFR ≥10%

In Step 2, more room homogeneity in terms of surrounding obstructions and fenestration size was implemented, by including only

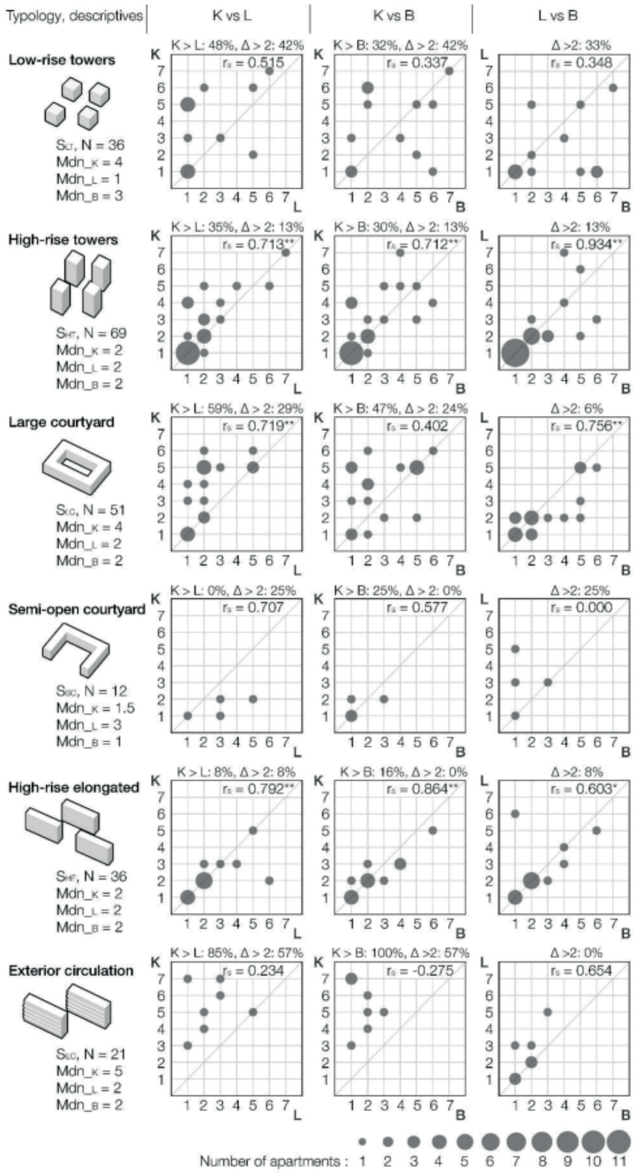


Fig. 9. Association between daytime electric lighting of different functions (K vs L, K vs B, L vs B) per building typology. The percentage of apartments where $\Delta > 2$ is shown above each scatterplot. The percentage of apartments where $K > L$ and $K > B$ is shown for the K vs L and K vs B scatterplots. Significant correlations are marked with * and ** ($p < 0.05$ and $p < 0.01$ respectively). The number of rooms (N) and median response (Mdn) per function are shown below each typology thumbnail.

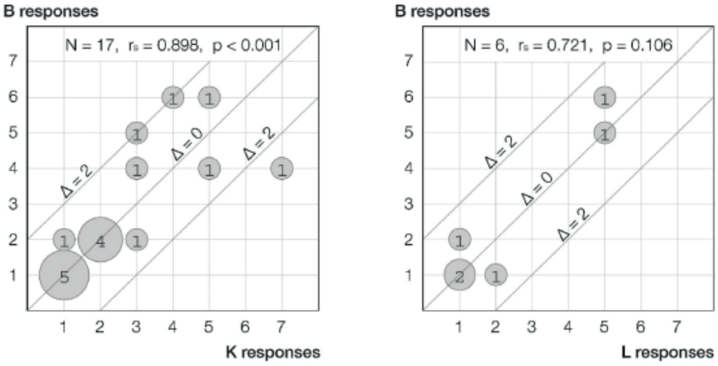


Fig. 10. Comparison of responses for B vs L, N = 17 (left) and B vs L, N = 6 (right). The labels in the markers indicate the number of apartments for a particular point on the scatterplot. The Spearman Rank Correlation coefficient r_S and the significance level p are shown above each plot.

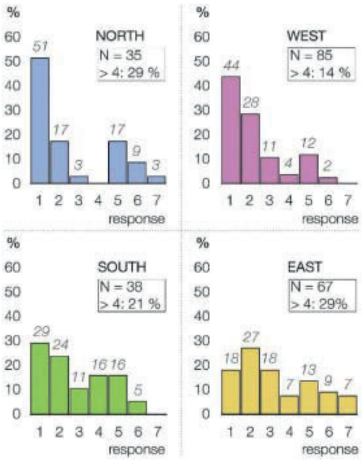


Fig. 11. Percentage histograms of responses on daytime electric lighting use for samples N_{19}, W_{21}, S_{18} and E_{30}.

rooms with VSC ≥15% & GFR ≥10%. Table 3 shows results of the Mann-Whitney tests performed for each pair of orientation samples $S_{N\_VSC\_GFR}$, $S_{W\_VSC\_GFR}$, $S_{S\_VSC\_GFR}$ and $S_{E\_VSC\_GFR}$, including the U statistic, significance level (*p*) and effect size (*r*). Two between-orientations differences were identified as significant: daytime electric lighting use was significantly less frequent for West-facing rooms ($S_{W\_VSC\_GFR}$: Mdn = 1.00) compared to East-facing rooms ($S_{E\_VSC\_GFR}$: Mdn = 2.50), U = 476.5, $p < 0.001$, with an effect size above medium ($r = 0.408 > 0.3$). In addition, daytime electric lighting use in West-facing rooms was significantly less frequent compared to South-facing rooms ($S_{S\_VSC\_GFR}$: Mdn = 2.00), U = 308.5, p = 0.006, with an effect size above medium ($r = 0.333 > 0.3$). No statistically significant differences were identified between other pairs of orientations. Overall, the West orientation was shown to differ most from all other orientations (Median response = 1), and mostly from East.

Table 3
Mann-Whitney Test statistic U, significance level p and effect size r from comparisons between samples $S_{N\_VSC\_GFR}$, $S_{W\_VSC\_GFR}$, $S_{S\_VSC\_GFR}$ and $S_{E\_VSC\_GFR}$. The upper row shows the sample size (N) and median response (Mdn) per sample.

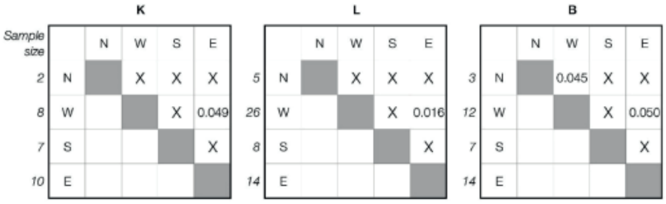
Sample	**$S_{N\_VSC\_GFR}$**	**$S_{W\_VSC\_GFR}$**	**$S_{S\_VSC\_GFR}$**	**$S_{E\_VSC\_GFR}$**
N (Mdn)	**10 (2.00)**	**46 (1.00)**	**22 (2.00)**	**38 (2.50)**
$S_{N\_VSC\_GFR}$	–	U = 179.5 p = 0.242 r = 0.156	U = 97.0, p = 0.588 r = 0.059	U = 153.5, p = 0.343 r = 0.137
$S_{W\_VSC\_GFR}$		–	U = 308.5, p = 0.006** r = 0.333*	U = 476.5, p < 0.001** r = 0.408*
$S_{S\_VSC\_GFR}$			–	U = 389.5, p = 0.654 r = 0.058
$S_{E\_VSC\_GFR}$				–

p: *, **. Correlation is significant at the 0.05 and 0.01 levels respectively (2-tailed).
r: *. Effect size is medium or larger.

Fig. 12 presents results per function K, L, B separately, where "X" indicates no significant difference between two orientations. The p value of the Mann-Whitney *U* Test is denoted only for cases where differences were statistically significant ($p < 0.05$). Orientation is denoted with N, W, S, and E, corresponding to North, West, South and East-facing rooms. Sample sizes per orientation are shown on the left side of each function matrix. The results verify the findings in Table 3, and it is shown that the difference between West and East-facing rooms is significant consistently among all room functions ($p < 0.05$ in W vs E for all functions K, L, B). In addition, the West orientation for bedrooms was found significantly different compared to North, even though there were only three North-oriented bedrooms, which is worth noting, as differences must be very high for the Mann-Whitney *U* test to achieve significance with such a low sample size (N = 3). It should also be noted here that the West orientation consistently presented the lowest median response among all room function samples.

3.3.3. *Step 3 – Effect of orientation considering identical rooms*

In Step 3, the East and West orientations were compared for rooms identical in all aspects (Fig. 7). The distribution of responses in each



K

Sample size		N	W	S	E
2	N	▨	X	X	X
8	W		▨	X	0.049
7	S			▨	X
10	E				▨

L

		N	W	S	E
5	N	▨	X	X	X
26	W		▨	X	0.016
8	S			▨	X
14	E				▨

B

		N	W	S	E
3	N	▨	0.045	X	X
12	W		▨	X	0.050
7	S			▨	X
14	E				▨

Fig. 12. Mann Whitney Test p value wherever significant ($p < 0.05$) for pairs of orientations, per room function K, L, B.

room sample is shown in Fig. 13, along with the median response per sample (Mdn) and the building typology. It is evident that for all typologies and functions, West-facing rooms reported significantly less daytime electric lighting use compared to their East counterparts. In retrospect, the difference between these two orientations was consistently confirmed in every step of analysis (Step 1, 2 and 3). This can logically be related to occupancy patterns within residential spaces, where it is more probable that an apartment is occupied from afternoon hours and onwards, when the sky is brighter at its western-most part, owing to the diurnal solar path. The potential savings in electricity regarding West can also be deducted from previous research in 400 Swedish households, where the hourly lighting load in a day (both weekdays and weekends) was shown to increase dramatically starting from approximately 15:00 [29]. This was shown to be true for all studied types of occupants (single, couple without children, family) and for a high range of ages (28–64 and 64+).

4. Discussion

Occupancy patterns were not queried in this study. Occupancy was assumed as increasing from afternoon hours and onwards. This is supported by multiple studies that have developed occupancy profiles based on statistical data, both internationally [33,38–41] and in the Swedish context [17–19]. The timeframe of the question regarding electric lighting use was one year, which is long enough to correspond to average behavior, which relates to the occupancy profile suggested by the aforementioned studies (typically increasing from the afternoon and onwards). This pattern is also in agreement with what was found here, as electric lighting use was shown to be significantly less frequent in rooms with West-oriented facades compared to East-oriented facades.

There are confounding factors pertaining to individual occupant differences that cannot be controlled when using self-administered questionnaires. For instance, a pro-environmental attitude may result in an occupant embracing a more energy-saving behavior. In addition, there are known differences in individual preferences for illuminance [42–44]. Random variations notwithstanding, the study included a sufficient amount of participants to decrease random noise and to achieve statistical significance for the performed tests. There was also sufficient variation in age among participants, which is by far the most important factor affecting visual capacity [28].

Electric lighting use was self-reported as a frequency measurement. In essence, the question requires an estimate pertaining to past behavior. The accuracy of responses is thus dependent on the ability to retrieve memories, so there is noise to be expected. However, three factors act in favor of the accuracy in this estimate. Firstly, electric lighting use is a habitual task, repeated on a daily basis, which makes it easier to memorize. Secondly, it is connected to cues such as conducting specific tasks (e.g. cooking at specific times) or occupying specific rooms during specific times. The association with such cues in the environment makes it easier to retrieve long-term memories through so-called retrieval cues [45]. Retrieval is further facilitated by the fact that responding takes place in the same room as the room where the habit takes place, which can yield context-dependent retrieval [46].

Any inference to the population is dependent on adequate sampling methods. To ensure that results can be generalized for apartment buildings, buildings were carefully selected to represent typical Swedish apartment blocks, according to Swedish urban planning history [22,23]. The typologies used in the study constitute an adequate sampling frame

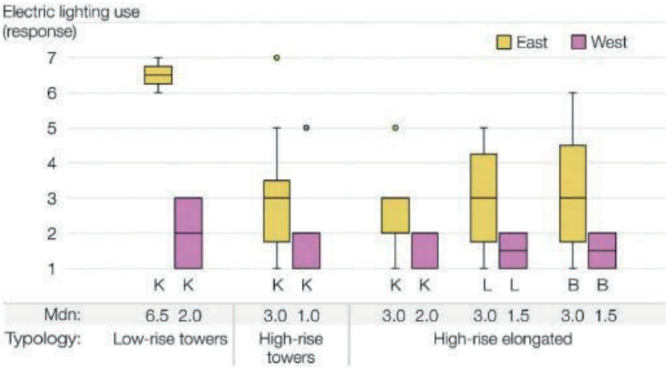


Fig. 13. Distribution of responses for paired samples of rooms identical in all aspects apart from orientation (East or West). The function, the median response and the building typology are shown below each box plot.

for Swedish apartments. However, different results may apply to rooms with significantly different dimensions compared to the values presented in Table 1.

5. Conclusions

This research evaluated the effect of room function and orientation on daytime electric lighting use in residential spaces. At the same time, the confounding effect of room geometry was monitored by gradually increasing the geometric homogeneity of analyzed rooms. The following can be concluded from this study:

5.1. Effect of rooms characteristics on occupant behavior

Although individual behaviors can be expected, the diversity in electric lighting use among occupants was shown to decrease depending on the physical environment. Overall, when comparing responses of different occupants living in identical rooms, it was shown that the Mean Absolute Deviation of responses did not exceed 1.5 point on the seven-point Likert scale used. A consistent finding was that differences between occupants were lower for West-facing rooms, for all room functions and building typologies. This is an important finding, as it suggests that electric lighting use is not random or completely dependent on individual preferences, but can be dictated by architectural design.

5.2. Room function

Electric lighting use is indeed associated with specific geometric features and not room function per se. For the total sample of rooms, it was found significantly more frequent in kitchen rooms ($p < 0.001$). However, when comparing different functions that had otherwise identical architectural features, no significant difference was found. However, the initial finding relates to the fact that kitchens had statistically the lowest glass-to-floor ratio (GFR) among room functions in all building typologies, the GFR value not diverging from the present national daylight recommendation of GFR $\geq$ 10% [35,47]. In other words, kitchens are designed strictly following minimum requirements, while other functions enjoy more generous fenestration sizes. This implies that design guidelines have the potential to decrease electricity used for lighting in kitchens. Perhaps recommendations should include higher daylight benchmarks for this function, considering its high lighting load compared to other rooms [29], and the potential daylight utilization due to the time-of-day it is occupied [33].

5.3. Room orientation

With respect to room orientation, the most concrete finding of this work is that West-facing rooms use daytime electric lighting less frequently compared to East-facing rooms. This was verified in all three steps of analysis, i.e. both for broad samples of diverse rooms and for narrow samples of identical rooms. The implications of this finding range from general orientation guidelines relative to room function, to specific formulations of criteria, e.g. a daylight performance indicator for residential spaces could perhaps account for orientation by focusing on a particular period of the day, the period leaning towards afternoon hours. Relative to this, the results imply that climate-based criteria [48–50] are more suitable for predicting potential electric lighting use savings, compared to the current quantified daylight criterion in the Swedish building code [35,47], which is founded on the Daylight Factor basis.

Funding

This research was funded by the Swedish Energy Agency (Energimyndigheten, grant nr 41816-2), Arkus (Stiftelsen Arkus) and ARQ (c/o White Architects AB, grant nr 12:2016).

Declaration of competing interest

None.

Acknowledgements

The authors are indebted to all residents who gave their responses, which were crucial for this research. We also thank the housing companies (MKB, HSB, Stena Fastigheter and Riksbyggen) who have generously contributed to this work by contacting their tenants. Thorbjörn Laike is acknowledged for his valuable comments regarding the structure of the questionnaire. Special thanks to Marwan Abugabbara and Ludvig Haav for undertaking the Arabic and English translation of the questionnaire respectively.

References

[1] P. Boyce, C. Hunter, O. Howlett, The Benefits of Daylight through Windows, Lighting Research Center Rensselaer Polytechnic Institute, New York, 2003, p. 88.
[2] M. Boubekri, Daylighting, Architecture and Health: Building Design Strategies, first ed., Architectural Press, Oxford, 2008.
[3] W.J.M. Van Bommel, G.J. Van den Beld, Lighting for work: a review of visual and biological effects, Light. Res. Technol. 36 (4) (2004) 255–268.
[4] J.A. Veitch, Living - to your good health - lyset og det gode helbred, Report NRC Publications Archive, also published in Arkitekten 9 (2007) 60–63, 2007.
[5] R. Hobday, The Light Revolution, first ed., Findhorn Press, Forres, 2006.
[6] S. Kunkel, E. Kontonasiou, A. Arcipowska, F. Mariottini, B. Atanasiou, Indoor Air Quality, Thermal Comfort and Daylight - Analysis of Residential Building Regulations in Eight EU Member States, Buildings Performance Institute Europe (BPIE), 2015, p. 100.
[7] CEN, European Standard EN 17037:2018 Daylight in Buildings, 2018, p. 77.
[8] IES, LM-83-12, Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), Illuminating Engineering Society, New York, US, 2012, p. 14.
[9] SGBC, BREEAM-SE 2017 1.1, Sweden Green Building Council, 2017, p. 432.
[10] SGBC, Miljöbyggnad 3.1, Swedish Green Building Council, 2020, p. 63.
[11] J. Mardaljevic, L. Heschong, E. Lee, Daylight metrics and energy savings, Light. Res. Technol. 41 (3) (2009) 261–283.
[12] J.A. Veitch, R. Gifford, Assessing Beliefs about Lighting Effects on Health, Performance, Mood, and Social Behavior, Environment and Behavior 28 (4) (1996) 446–470.
[13] J.A. Veitch, D.W. Hine, R. Gifford, End-users' knowledge, beliefs and preferences for lighting, J. Interior Des. 19 (2) (1993) 15–26.
[14] I. Bournas, M.-C. Dubois, Daylight regulation compliance of existing multi-family apartment blocks in Sweden, Build. Environ. 150 (2019) 254–265.
[15] N.E. Klepeis, W.C. Nelson, W.R. Ott, J.P. Robinson, A.M. Tsang, P. Switzer, J. V. Behar, S.C. Hern, W.H. Engelmann, The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants, J. Expo. Sci. Environ. Epidemiol. 11 (3) (2001) 231–252.
[16] SCB, Statistics Sweden - Swedish Time Use Survey 2010/11, 2012-07-02.
[17] D. Johansson, H. Bagge, L. Lindstrii, Measured occupancy levels in 18 Swedish apartment buildings - application to input data for building simulations, 12th Conference of International Building Performance Simulation Association, Proceedings of Building Simulation (2011) 1730–1736. Sydney, 14-16 November.
[18] J. Widen, A.M. Nilsson, E. Wackelgard, A combined Markov-chain and bottom-up approach to modelling of domestic lighting demand, Energy Build. 41 (10) (2009) 1001–1012.
[19] J. Widén, M. Lundh, I. Vassileva, E. Dahlquist, K. Ellegård, E. Wäckelgård, Constructing load profiles for household electricity and hot water from time-use data—modelling approach and validation, Energy Build. 41 (7) (2009) 753–768.
[20] SCB, Statistics Sweden - Dwelling Stock 31/12/2017, 2018.
[21] SCB, Statistics Sweden - Completed Dwellings and Number of Rooms Including Kitchen in Newly Constructed Buildings by Region and Type of Building, 2019. Year 1975 - 2018.
[22] T. Hall, M. Rörby, Stockholm: the Making of a Metropolis, Routledge, Taylor & Francis e-Library, 2009.
[23] J. Rådberg, A. Friberg, Svenska Stadstyper : Historik, Exempel, Klassificering, Stockholm : KTH högskoletr., Stockholm, 1996, 1996.
[24] P. Littlefair, Daylight, sunlight and solar gain in the urban environment, Sol. Energy 70 (3) (2001) 177–185.
[25] I. Bournas, M.-C. Dubois, T. Laike, Perceived daylight conditions in multi-family apartment blocks – instrument validation and correlation with room geometry, Build. Environ. 169 (2019), 106574.
[26] H. Wilhite, A cross-cultural analysis of household energy use behaviour in Japan and Norway, Energy Pol. 24 (9) (1996) 759–803.
[27] R. Wall, T. Crosbie, Potential for reducing electricity demand for lighting in households: an exploratory socio-technical study, Energy Pol. 37 (3) (2009) 1021–1031.
[28] P.R. Boyce, Human Factors in Lighting, third ed., CRC Press, Taylor & Francis Group, London, 2017.

[29] Z.P. Zimmermann, End-use Metering Campaign in 400 Households in Sweden. Assessment of the Potential Electricity Savings, Swedish Energy Agency, Eskilstuna, 2009, p. 344.

[30] C. Leys, C. Ley, O. Klein, P. Bernard, L. Licata, Detecting outliers: do not use standard deviation around the mean, use absolute deviation around the median, J. Exp. Soc. Psychol. 49 (4) (2013) 764–766.

[31] G.V. Glass, K.D. Hopkins, Statistical Methods in Education and Psychology, third ed., Allyn and Bacon, Boston, 1995.

[32] K.M. Gerhardsson, T. Laike, M. Johansson, Residents' lamp purchasing behaviour, indoor lighting characteristics and choices in Swedish homes, Indoor Built Environ. 28 (7) (2019) 964–983.

[33] S. Wolf, D. Calì, M.J. Alonso, R. Li, R.K. Andersen, J. Krogstie, H. Madsen, Room-level occupancy simulation model for private households, J. Phys. Conf. 1343 (2019), 012126.

[34] P. Littlefair, Site layout planning for daylight and sunlight - a guide to good practice, in: Building Research Establishment, IHS BRE Press, Watford, 1991.

[35] BOVERKET, Boverket's building regulations - mandatory provisions and general recommendations, BFS 2011:6 with amendments up to BFS 2018:4, 2018.

[36] R. Rosenthal, Meta-analytic procedures for social science research sage publications: beverly hills, 1984, 148 pp, Educ. Res. 15 (8) (1986) 18.

[37] J. Cohen, Statistical Power Analysis for the Behavioral Sciences, second ed., Lawrence Erlbaum Associates, New York, 1988.

[38] D. Mitra, N. Steinmetz, Y. Chu, K.S. Cetin, Typical occupancy profiles and behaviors in residential buildings in the United States, Energy Build. 210 (2020).

[39] R. El Kontar, T. Rakha, Profiling occupancy patterns to calibrate urban building energy models (UBEMs) using measured data clustering, Technology Architecture + Design 2 (2) (2018) 206–217.

[40] V.M. Barthelmes, R. Li, R.K. Andersen, W. Bahnfleth, S.P. Corgnati, C. Rode, Profiling occupant behaviour in Danish dwellings using time use survey data, Energy Build. 177 (2018) 329–340.

[41] S. Hu, D. Yan, J. An, S. Guo, M. Qian, Investigation and analysis of Chinese residential building occupancy with large-scale questionnaire surveys, Energy Build. 193 (2019) 289–304.

[42] G.R. Newsham, M.B.C. Aries, S. Mancini, G. Faye, Individual control of electric lighting in a daylit space, Light. Res. Technol. 40 (1) (2008) 25–41.

[43] P.R. Boyce, N.H. Eklund, S.N. Simpson, Individual lighting control: task performance, mood and illuminance, J. Illum. Eng. Soc. 29 (1) (2000) 131–142.

[44] T. Moore, D.J. Carter, A. Slater, Long-term patterns of use of occupant controlled office lighting, Light. Res. Technol. 35 (1) (2003) 43–59.

[45] E.B. Goldstein, Cognitive Psychology : Connecting Mind, Research, and Everyday Experience, fourth ed., Cengage Learning, 2014.

[46] D.R. Godden, A.D. Baddeley, Context dependent memory in two natural environments: on land and underwater, Br. J. Psychol. 66 (3) (1975) 325–331.

[47] SIS, i Standardiseringskommissionen, Sverige - SVENSK STANDARD SS 91 42 01 (1988).

[48] J. Mardaljevic, M. Andersen, N. Roy, J. Christoffersen, Daylighting Metrics: Is There a Relation between Useful Daylight Illuminance and Daylight Glare Probabilty?, Building Simulation and Optimization Conference BSO12, Loughborough, UK, 2012.

[49] J. Mardaljevic, J. Christoffersen, 'Climate connectivity' in the daylight factor basis of building standards, Build. Environ. 113 (2017) 200–209.

[50] P. Tregenza, J. Mardaljevic, Daylighting buildings: standards and the needs of the designer, Light. Res. Technol. 50 (1) (2018) 63–79.

Paper 6

Paper 6

LEUKOS
The Journal of the Illuminating Engineering Society

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ulks20

Association between Perceived Daylit Area and Self-reported Frequency of Electric Lighting Use in Multi-dwelling Buildings

Iason Bournas

To cite this article: Iason Bournas (2021): Association between Perceived Daylit Area and Self-reported Frequency of Electric Lighting Use in Multi-dwelling Buildings, LEUKOS, DOI: 10.1080/15502724.2020.1851606

To link to this article: https://doi.org/10.1080/15502724.2020.1851606

LEUKOS
https://doi.org/10.1080/15502724.2020.1851606

Association between Perceived Daylit Area and Self-reported Frequency of Electric Lighting Use in Multi-dwelling Buildings

Iason Bournas

Division of Energy and Building Design, Department of Architecture and Built Environment, Lund University, Lund, Sweden

ABSTRACT

This paper examines the association between daytime electric lighting use and perceived indoor daylight availability in residential spaces. In addition, occupant preferences were evaluated, in particular which rooms are prioritized in terms of daylight availability. The study deployed a questionnaire survey that was carried out in typical multi-dwelling apartment blocks in Malmö, Sweden (Latitude: 55.6 °N). Occupants were asked to report how often they use electric lighting during daylight hours (EL) in their kitchen, living room and main bedroom, and how much of the floor area they perceive as adequately daylit (DA) throughout the year. Responses EL and DA were measured in seven-point semantic differential scales, and were correlated (Spearman) to evaluate their association for different room groups. Groups were based on age, room function, façade orientation, balcony obstruction and fenestration geometry. In addition, occupants were asked which room they would choose if there had to be one underlit room. Results indicate that EL is strongly associated with DA in the overall room sample ($r_S = -0.588$, $p < .01$, $n = 225$). The association is persistent across room groups of different characteristics, with the Spearman rank correlation coefficient ranging between −0.4 and −0.8, and not differing significantly between groups. In terms of preferences, a significantly high proportion of participants would choose the bedroom if there had to be one underlit room (62%, $p < .05$), while the kitchen was selected by only 5 out of 108 respondents.

ARTICLE HISTORY
Received 22 March 2020
Revised 31 October 2020
Accepted 11 November 2020

KEYWORDS
Electric lighting; daylight; survey; residential; preferences

1. Introduction

There are several good reasons to minimize the use of electric lighting in residential spaces by utilizing more daylight to illuminate room interiors (Knoop et al. 2019). Firstly, it has long been shown that daylight has substantial healthcare effects (Beauchemin and Hays 1998; Ulrich 1991; Walch et al. 2005; Weiss et al. 2016). It is the most important among "zeitgebers" ("time givers", in German) that help brain neurons synchronize with the environment in a 24-hour rhythm that affects human physiology and behavior, ensuring health and well-being (Arendt and Middleton 2018; Kyriacou and Hastings 2010). For instance, sleep-wake cycles, alertness, cognitive performance, core body temperature and hormone production are all dictated by an internal time-keeping system in the suprachiasmatic nucleus of the hypothalamus (Czeisler and Gooley 2007). On the other hand, the absence of daylight is associated with seasonal affective disorder (Menculini et al. 2018), increased stress levels (Stevens and Rea 2001) and inability to generate vitamin D (Mead 2008). Secondly, electricity used for lighting adds up to the overall energy use of a residence, resulting in increased greenhouse gas production. Exacerbating the situation for Swedish dwellings is the fact that they are equipped (on average) with 35 lamps per dwelling, the highest among 12 EU countries according to a previous market study (PremiumLight Project Consortium 2014). Thirdly, occupants tend to prefer daylight to electric lighting (Veitch et al. 1993). Its spectral composition along with its variation during the day and season allow people to detect all subtle color shifts, to estimate the time of the day, to be aware of the weather conditions, in essence, to connect to their surrounding environment. It is also the predominant factor of how space is revealed and perceived by its users (Lam 1986). The preference to daylight is partly attributed to the fact that it necessitates the existence of fenestration. In Denmark, in a study including 1823 office workers,

---

CONTACT Iason Bournas iason.bournas@ebd.lth.se Division of Energy and Building Design, Department of Architecture and Built Environment, Lund University, Box 118, Lund SE-221 00, Sweden.

Supplemental data for this article can be accessed on the publisher's website.

participants reported that the most positive aspects of windows were *to be able to see out, to see the weather outside, and to be able to open the window* (Christoffersen and Johnsen 1999, 41). Of these and other benefits of daylight (Boyce 2017), the present work focuses on the potential of daylight to reduce unnecessary electricity for lighting.

The hypothesis that electric lighting use can be affected by indoor daylight availability in dwellings can be logically deducted from the fact that dwellings i) are occupied during part of the daylight hours of the year and ii) are using electric lighting during that period. The fact that domestic occupancy in Sweden takes place during daylight hours has been shown previously by measurements of airflow rates in ventilation systems and carbon dioxide concentrations in 342 apartments (Johansson et al. 2011). In addition, the latest Swedish Time Use Survey derived hourly occupancy and activity profiles showing that people in Sweden are very likely to be inside their dwellings during afternoon hours (SCB 2012), when daylight is still available from the sun and sky. Similar to occupancy, the fact that people do use electric lighting during daylight hours can be traced to previous research. A metering campaign in 400 Swedish dwellings showed that the hourly lighting load (both weekdays and weekends) increases dramatically starting from approximately 15:00 for all types of occupants (single, couple without children, family) and for a high range of ages (28– 64 and 64+) (Zimmermann 2009). A multitude of further Swedish and international studies are in agreement that lighting use increases noticeably after 15:00 hours (Barthelmes et al. 2018; El Kontar and Rakha 2018; Hu et al. 2019; Johansson et al. 2011; Mitra et al. 2020; Stokes et al. 2006; Widén et al. 2009a, 2009b; Wolf et al. 2019).

From the aforementioned information, we can infer that for a significant part of the year, electric lighting in the residential sector is used before sunset, when daylight is still available. This lighting use can be expected to increase, if we consider developing trends of remote work (work-from-home), owing to advances in telecommunications (GWA 2020; Hardill and Green 2003). The same is true for situations similar to the ongoing coronavirus (COVID-19) pandemic, which caused massive relocations of people to their homes in order to work safely and limit the spread of the virus (Hickman and Saad 2020).

1.1. Objective

Due to the benefits of daylight, a considerable amount of standards, regulations and certification schemes include provisions for indoor daylight availability, e.g. EN17037 (CEN 2018). However, the potential to reduce residential electricity for lighting by means of daylight utilization has been challenged by previous work, stating that the use of artificial lighting *seems to be largely independent from the availability of natural light*, owing to individual occupant habits and preferences regarding electric lighting (Lobaccaro et al. 2019, 1). On the contrary, another study proposing daylight performance indicators for residential spaces assumed that *good levels of daylight illuminances are likely to be associated with lower levels of electric lighting usage* (Mardaljevic et al. 2011, 6). In the present study, it was hypothesized that daytime is a period when the sun and sky may provide adequate illumination for some domestic activities (e.g. cooking or cleaning), resulting in occupants switching on lights less frequently if their dwellings are adequately daylit. Behavioral aspects notwithstanding, the present paper aims to demonstrate that daytime electric lighting use in residential spaces is indeed associated with indoor daylight availability. In addition, the study aims to identify (if any) preference among occupants, with respect to which room function is (or is not) prioritized in terms of daylight availability.

2. Material and methods

The study design involved six procedural steps that are schematically illustrated in Fig. 1, namely: i) selecting representative buildings, ii) distributing questionnaires, iii) collecting responses, iv) locating apartments of participants, v) characterizing apartments geometrically and vi) analyzing statistically the gathered data.

2.1. Selecting buildings and characterizing apartments

The survey was carried out in the city of Malmö (Latitude: 55.6 °N), and included six residential multi-dwelling developments (Fig. 2) located in the central and suburban area of the city. Apartments in multi-dwelling buildings are the most common type of dwellings in Sweden (51%) (SCB 2018), and the

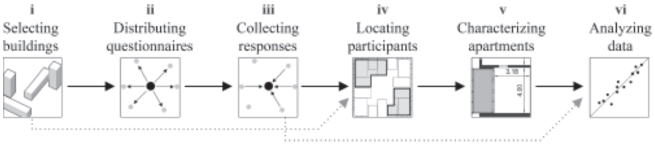
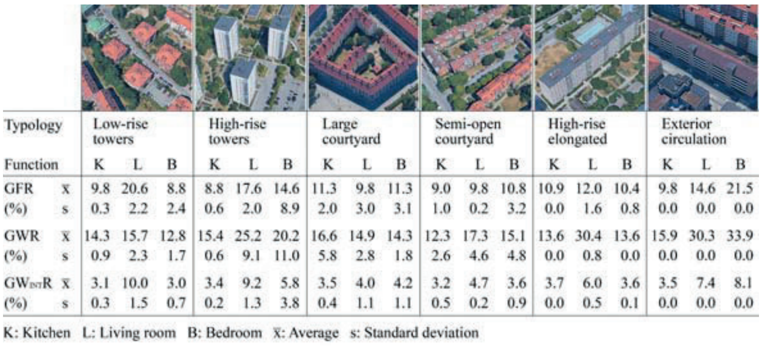


Fig. 1. Schematic workflow of the study design including six procedural steps.



Typology		Low-rise towers			High-rise towers			Large courtyard			Semi-open courtyard			High-rise elongated			Exterior circulation		
Function		K	L	B	K	L	B	K	L	B	K	L	B	K	L	B	K	L	B
GFR	x̄	9.8	20.6	8.8	8.8	17.6	14.6	11.3	9.8	11.3	9.0	9.8	10.8	10.9	12.0	10.4	9.8	14.6	21.5
(%)	s	0.3	2.2	2.4	0.6	2.0	8.9	2.0	3.0	3.1	1.0	0.2	3.2	0.0	1.6	0.8	0.0	0.0	0.0
GWR	x̄	14.3	15.7	12.8	15.4	25.2	20.2	16.6	14.9	14.3	12.3	17.3	15.1	13.6	30.4	13.6	15.9	30.3	33.9
(%)	s	0.9	2.3	1.7	0.6	9.1	11.0	5.8	2.8	1.8	2.6	4.6	4.8	0.0	0.8	0.0	0.0	0.0	0.0
$GW_{INT}R$	x̄	3.1	10.0	3.0	3.4	9.2	5.8	3.5	4.0	4.2	3.2	4.7	3.6	3.7	6.0	3.6	3.5	7.4	8.1
(%)	s	0.3	1.5	0.7	0.2	1.3	3.8	0.4	1.1	1.1	0.5	0.2	0.9	0.0	0.5	0.1	0.0	0.0	0.0

K: Kitchen L: Living room B: Bedroom x̄: Average s: Standard deviation

Fig. 2. Means (x̄) and standard deviations (s) for GFR, GWR and $GW_{INT}R$ per development and room function. Abbreviations K, L, B stand for Kitchen, Living room and Bedroom respectively. Map data: Google.

prevalent type among new constructions annually since 1985 (SCB 2019). The developments were chosen based on i) their block typology and ii) their construction year, to represent typical residential blocks as documented in Swedish urban planning history (Hall and Rörby 2009; Rådberg and Friberg 1996). The evaluated rooms included the kitchen (K), living room (L) and bedroom (B) as per the national building regulation, which stipulates that daylight should be provided *where people are present other than occasionally* (BOVERKET 2020a, 98).

Building drawings were retrieved from the municipal archive of Malmö (Malmö-Stad 2020), were re-drawn in CAD format and analyzed using Grasshopper (Grasshopper 2020) to deduct geometric attributes per room. Attributes included the glass-to-floor ratio (GFR), the glass-to-wall ratio (GWR) and the glass-to-internal wall ratio ($GW_{INT}R$), which is the ratio of the glazing area divided by the total interior walls area. The drawings were validated via on-site measurements taken in a sample of apartments (20% of apartments). It was found that the municipal archive drawings were up-to-date, except for a few cases with removed interior wall partitions. Figure 2 shows the six surveyed developments, along with means (x̄) and standard deviations (s) of the three geometric attributes per room function.

2.2. *Survey period and subjects*

The questionnaire was distributed on March 13, 2018, aiming for occupants to respond during a period close to the spring equinox. Indeed the vast majority of participants (90%) gave their responses between March 14 and March 28. Overall, 108 questionnaires were mailed back. Post-processing revealed that 28 were missing values while five questionnaires did not include all three room functions K, L, B (small apartments). The response rate was calculated to 13%, but it was confirmed that there was satisfactory variation in age and gender among participants (Fig. 3). Sufficient variation in age is important, as it is by far the most common cause of limited visual capacity (Boyce 2017), as well as an influencing factor of

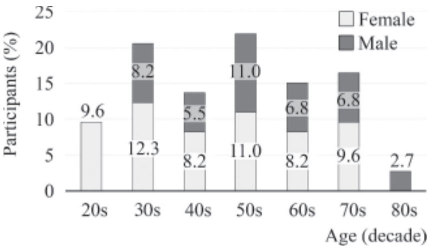


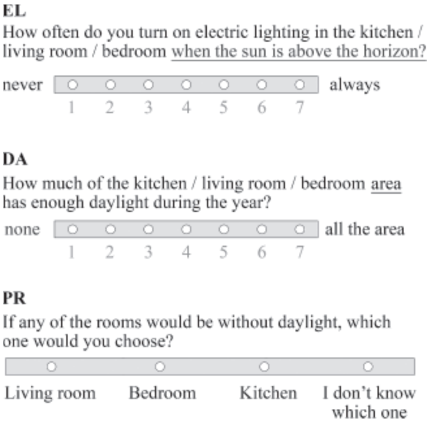
Fig. 3. Percentage of participants per age group and gender.

electric lighting use in Swedish residential spaces during the day (Zimmermann 2009).

The main procedure used to provide a quantitative subjective evaluation of the rooms was semantic differential (SD) scales. Two SD scales were used for each room function as shown in Fig. 4 (EL & DA). A third item was included at the end of the questionnaire as a multiple-choice question with a single-answer option (PR). The reader may refer to the Supplemental Material for the complete questionnaire; this includes additional items that were used in a previous publication and are irrelevant to the present study. The EL item aimed to measure the frequency of electric lighting use during the daylight hours of the year (EL). The DA item aimed to measure the portion of the room area that is sufficiently daylit throughout the year. The PR item aimed to assess occupant preferences, in particular, which room would be tolerated without daylight if there had to be one such room. Due to missing EL and DA data in some questionnaires, the processed responses for EL and DA were 75 per room function (75 apartments, 225 rooms), and PR responses were 108 (108 apartments). During processing, the EL response was quantified with an index ranging from 1 = "never" to 7 = "always", and similarly, the DA response from 1 = "none" to 7 = "all the area", as shown indicatively below the scales in Fig. 4.

2.3. Questionnaire design

Previous work on semantic differential scales indicates that different participants may use the same scale to assess different aspects of the physical environment (Houser and Tiller, 2003). The design and formulation of items can influence responses (Lietz


EL

How often do you turn on electric lighting in the kitchen / living room / bedroom when the sun is above the horizon?

never ○ ○ ○ ○ ○ ○ ○ always
1 2 3 4 5 6 7

DA

How much of the kitchen / living room / bedroom area has enough daylight during the year?

none ○ ○ ○ ○ ○ ○ ○ all the area
1 2 3 4 5 6 7

PR

If any of the rooms would be without daylight, which one would you choose?

○ Living room ○ Bedroom ○ Kitchen ○ I don't know which one

Fig. 4. Questionnaire items: i) EL, the self-reported frequency of daytime electric lighting use throughout the year, ii) DA, the perceived area portion that is adequately daylit over the year and iii) PR, the preferred room function to be underlit, if there had to be one.

2010). Tiller and Rea (1992) have previously advocated that ambiguous use of semantic differential scales can be prevented by adequately defining i) the response measure, and ii) the dimensions of the response. The items in Fig. 4 were formulated accordingly, in order for every participant to assess the same aspect of the environment, with the same measurement scale.

2.3.1. Definition of response measure

On a basic level, the participant is required to know the semantic meaning of the words used in the items. On a higher level, the aspect to be assessed should be comprehended. In the case of the EL item, the clause "you turn on electric lighting" is a clear concept. The term "how often" can be intuitively understood as a measure of frequency. Observing the extreme adverbs of frequency at the ends of the response scale (never, always) facilitates understanding. The reference period was the daylight hours of the year. To avoid confusion of the term "daytime" with a potential working schedule (e.g. 8:00– 17:00), the underlined clause "when the sun is above the horizon" was used instead (Fig. 4). In the case of the DA item, two segments of the question needed to be salient: the part "how much of the … area" that refers to an area measure and the part "enough daylight" that refers to preferred daylight levels. When in the context of rooms, the Swedish word used for the term "area" (yta) is semantically connected to the "floor area", i.e. refers to a region on the horizontal plane whose boundaries are defined by the room walls. The Swedish words used for "how much of" (the area) were "hur stor del av" (yta), the literal translation being "how big part of" (the area), which inherently refers to a portion of area, a fraction of the total space. The term "all the area" at the right end of the scale further clarifies this. The Swedish term used for "enough", "tillräckligt med", is the generic term for "sufficient amount of" or "adequate amount of". In conjunction with "daylight", it connotes daylight sufficiency in order to conduct a task (e.g. reading, cooking, etc.). "Tillräckligt med dagsljus" (enough daylight) is the official terminology used by Boverket, the state authority that issues Swedish building regulations, to refer to adequate amounts of daylight (BOVERKET 2020b).

2.3.2. Definition of response dimensions

To ensure that the response magnitude was measured consistently by participants, it was important that the terms at the ends of the scales were bipolar opposites that could define the entire range of possible measures. The two terms at the sides of each scale were also equidistant from the neutral central point (rating 4). The EL response was bounded by the terms "never" and "always", as frequency is normally considered to vary along these two terms. For DA, the terms "none" and "all the area" were used, as they define all possible dimensions, ranging from the smallest possible to largest possible amount of room area.

2.3.3. Additional instructions for participants

A pilot study was conducted prior to collecting data, with nine subjects from the author's work environment, to ensure that individual items operate well, but also to verify that the questionnaire as a whole was appropriately structured. Informal interviews with the nine participants indicated that the DA area was consistently understood as the area "satisfactorily lit" or "bright enough". However, the extent of area under evaluation was unclear in cases where the kitchen was not separated from the dining room or the living room by a wall partition. Therefore, additional instructions were included per room function, as shown in the questionnaire found in the Supplemental Material. For instance, the kitchen items were preceded by the clarification: "*The 'kitchen' is considered the area around the kitchen cabinets. A dining area away from the kitchen cabinets should not be considered for the following questions*". For the living room, it was clarified that "*If the apartment has one kitchen and only one other room, then that room should be considered the 'living room'* ". This instruction was included to guide participants living in apartments that did not have a separate bedroom, i.e. sleeping occurs in the same space as the living room activities (small apartments). However, the present study did not assess any such apartment. Finally, for the bedroom, it was clarified that "*If the apartment has more than one bedrooms, then answer the following questions ONLY for the largest bedroom*". There were two reasons for this decision. The first reason was that in case of multiple bedrooms, the largest bedroom (main bedroom) was expected to correspond to the main tenant of the apartment, for instance to the parent instead of the child, who was also expected to be the responder. The second reason was that the room would need to be identified (among other bedrooms) on the plan of the apartment during post processing (Fig. 1-iv, *Locating participants*). In the following sections of this paper, the term "bedroom" stands for "the main bedroom", i.e. the largest bedroom in the apartment.

2.3.4. Retrieval from memory

Both EL and DA items ask retrospective questions, i.e. they refer to a period preceding the survey. The EL item asks participants to construct an estimate of absolute frequency, which is meant to characterize lighting use throughout the year. In other words, participants have to reflect on past behavior within a long period to provide a response. The response accuracy is thus dependent on the ability to retrieve memories, which means that noise can be expected. However, three factors in this study design may improve the accuracy in this estimate. Firstly, electric lighting use is repeated on a daily basis, as a habitual task, which facilitates memorization. Secondly, there are cues connected to this habit such as domestic tasks (e.g. cooking at specific times) or room occupancy patterns (e.g. being in specific rooms at specific times). The association with such cues in the environment facilitates the retrieval of long-term memories through so-called retrieval cues (Goldstein 2014). Retrieval is further facilitated by the fact that responding takes place in the same room as the room where the habit takes place, which can yield context-dependent retrieval (Godden and Baddeley 1975). Thirdly, the survey was conducted during a period that represents "average" daylight conditions (spring equinox). This effectively means that even if a participant were to base his or her answer on recent behavior to provide a response (e.g. within two weeks prior to the survey), this behavior would be during a period of typical daylight availability and average daytime duration with respect to the entire year. The same factors (i.e. cues, context, and time of survey) facilitate responding to the DA item, with the difference that the response relies on retrieving memories of the space, instead of memories of behavior in it.

2.3.5. Inattentive responding

Inattentive responding, also known as careless responding, refers to participants responding to items without regard to what is actually being asked. Meade and Craig (2012) have identified four factors affecting careless responding: respondent interest, survey length, social contact and environmental distraction. Inattentive responses can also be expected from occupants who have no prior experience upon which to base their response (Fotios 2019), for instance tenants that moved recently into the apartment and have not lived there long enough to make an informed estimate. Several strategies were used to alleviate inattentive responding. There was an introductory page explaining the importance of daylight and the significance of the collected data, i.e. potential influence on policy making. The latter was also meant to instill a sense of responsibility for the answers provided. The overall questionnaire length was kept to a minimum (two pages) to avoid attention waning over the course of a lengthy process. The fact that participation was voluntary was stated twice, in order to avoid a sense of obligation to participate. There was also no monetary incentive (or other form of retribution), which could potentially motivate a person to participate regardless of lacking knowledge or experience upon which to base his or her response.

2.3.6. Context effects

Literature on survey context effects has previously shown that preceding items can affect responses to subsequent items (Strack and Martin 1987). This could happen in two cases in this study: i) a response for the first room appearing in the questionnaire could affect a response for the following room and ii) the EL response could affect the DA response for a given room. To avoid the first case, the EL and DA items for each room function (kitchen, living room and bedroom) were placed in separate sections of the questionnaire. These sections were separated from each other by distinct headings, instructions and visual markers. They were also separated by seven additional items and fill-in instructions per room, and the occupant was asked to enter each room prior to responding to items for it (see Supplemental Material for complete questionnaire). Effects between the EL and DA items were alleviated by formulating questions to refer to different contexts. The EL item asks for a response on previous behavior (activity of turning lights on, "how often"), while the DA item refers to previous visual perception (experience of space, "how big an area"). In addition, different formulations were used for the reference period (EL: "when the sun is above the horizon", DA: "during the year"). These differences along with a salient definition of each item ensure understanding of each response measure and prevent the two items from being perceived as parts of the same context or sequence (whole – part), alleviating assimilation and contrast effects (Schwarz et al. 1991; Tourangeau and Rasinski 1988).

2.3.7. The preference item PR

The third item in Fig. 4 regarded occupant preferences (PR), in particular, which room would be tolerated without daylight, if there had to be one such room. This item aimed at revealing (if any) popular prioritization with respect to daylight availability. This prioritization may be useful in devising design guidelines, considering constraints pertaining to multi-dwelling buildings as opposed to single-family (detached) houses. For instance, there is a high probability that a room is placed deeper into the building core and away from the exterior wall if facades are not extensive enough to arrange all rooms along the perimeter of the building (deep plan buildings). There is also no possibility to utilize skylights for rooms far from the façade, except in apartments on the top floor. The first three choices for the PR response corresponded to the three room functions. A fourth choice was given as an option, (response: "I don't know which one"). This response includes all those occupants that cannot make a clear distinction, due to any of the following three reasons: i) because they value daylight equally for all functions, ii) because they would not accept any room being underlit, iii) because the room they would choose was not included in the questionnaire (e.g. bathroom).

2.4. Types of electric lighting use

Electric lighting use in each room was assigned a specific "type", based on the relation between the EL and DA responses. In essence, the concept of categorizing electric lighting use into different "types" was based on whether or not the user responds to available daylight levels by using electric lighting accordingly. The Euclidean distances between responses EL, DA and the scale midpoint (rating = 4) were calculated to define five types of use (Table 1). The use was assumed *responsive* when the EL response was the reverse of the DA response with respect to the scale midpoint (EL = 8 – DA), namely: 1v7, 2v6, 3v5, 4v4, 5v3, 6v2, 7v1. This type characterizes electric lighting use that is responsive to daylight availability, i.e. the lighting switch-on behavior corresponds to daylight levels. If electric lighting is normally off in a very bright space, this is considered *responsive* by the study. The latter implies that *responsive* use is not determined by the degree of electric lighting use, but by its association with perceived daylit area (DA). The second type of use, termed *responsive ±1*, was assigned when responses deviated from *responsive* by a distance of ± 1 on the rating scale (EL = (8 – DA) ±1), for instance 1v6 instead of 1v7, 2v7 instead of 2v6 etc. Similarly, the *responsive* ±2 use was assigned when responses deviated from *responsive* by a distance of ± 2 on the rating scale (EL = (8 – DA) ±2). The three aforementioned types of use (*responsive* types) did not include rooms with both responses greater than 4 or both lower than 4. In other words, *responsive* types of use are characterized by a negative correlation between EL and DA. On the contrary, the fourth and fifth types included combinations where EL and DA were positively correlated. More specifically, the fourth group included rooms where occupants reported higher frequencies of electric lighting use and larger extents of daylit area. The use in these rooms was considered irresponsive, since electric lighting is used despite the large extent of the daylit area (EL ≥ 4 and DA ≥ 4, excluding the pair with EL = DA = 4). This type was termed *irresponsive EL↑-DA↑*. On the other hand, in some cases electric lighting use was reported as infrequent although only a small daylit area was reported. The electric lighting use in these rooms was termed *irresponsive EL↓-DA↓* (EL ≤ 4 and DA ≤ 4, excluding the pair with EL = DA = 4), i.e. EL is low despite DA being low.

2.5. Evaluated room groups

The EL and DA responses were analyzed considering the overall room sample (S_{ALL}, N = 225), and groups

Table 1. Combinations of EL and DA responses for each type of use (49 in total).

Type of use	responsive	responsive ±1	responsive ±2	irresponsive EL↑-DA↑	irresponsive EL↓-DA↓
(EL, DA)	(1,7)	(1,6)	(1,5)	(4,7)	(1,4)
	(2,6)	(2,7)	(3,7)	(4,6)	(1,3)
	(3,5)	(2,5)	(5,1)	(4,5)	(1,2)
	(4,4)	(3,6)	(7,3)	(5,7)	(1,1)
	(5,3)	(5,2)		(5,6)	(2,4)
	(6,2)	(6,3)		(5,5)	(2,3)
	(7,1)	(6,1)		(5,4)	(2,2)
		(7,2)		(6,7)	(2,1)
				(6,6)	(3,4)
				(6,5)	(3,3)
				(6,4)	(3,2)
				(7,7)	(3,1)
				(7,6)	(4,3)
				(7,5)	(4,2)
				(7,4)	(4,1)
Combinations	7	8	4	15	15

extracted from it according to room function, occupant age, balcony obstruction, orientation, geometry and type of electric lighting use. The sizes of different groups are shown further down in the Results section to avoid repetition here. With respect to room function, there were three groups K, L, B, one per function (K: kitchen, L: living room and B: bedroom). With respect to age, rooms were divided into six groups according to ranges "< 30", "(30– 39)", "(40– 49)", "(50– 59)", "(60– 69)" and "≥ 70". With respect to balcony, rooms were divided into two groups, one group including rooms with a balcony obstruction above their fenestration, and one without (YES, NO, respectively). These groups only included rooms where the balcony obstructed all available fenestration area in order to assess the balcony impact, thus 196 out of 225 rooms were included. In terms of orientation, rooms were divided into groups N, W, S, E corresponding to North-facing, West-facing, South-facing and East-facing rooms respectively. The rationale for grouping rooms according to orientation was the azimuth angle of the room's fenestration normal, measured clockwise starting from North. Four distinct angular ranges were defined based on the mid-cardinal compass points, e.g. a room was considered East-facing for a façade normal direction between angles 45° and 135°, South-facing for a façade normal direction between angles 135° and 225° etc. In terms of geometry, rooms were dichotomized into two groups for each of the geometric attributes GFR, GWR, $GW_{INT}R$, one group including rooms with the lowest half of the attribute values and one group including rooms with the highest half. The comparison between low and high attribute groups were performed separately for each room function, as paired samples t-tests comparing GFR, GWR and $GW_{INT}R$ between the K, L, B groups revealed significant differences between function groups for all geometric attributes. Finally, seven groups of rooms were defined according to type of electric lighting use: i. *responsive* (only rooms with *responsive* use), ii. *responsive ±1* (only rooms with *responsive ±1* use), iii. *responsive ±2* (only rooms with *responsive ±2* use), iv. *irresponsive EL↑-DA↑* (only rooms with *irresponsive EL↑-DA↑* use), v. *irresponsive EL↓-DA↓* (only rooms with *irresponsive EL↓-DA↓* use), vi. *responsive OR responsive ±1* (rooms with either *responsive* or *responsive ±1* use) and vii. *irresponsive EL↑-DA↑ OR irresponsive EL↓-DA↓* (rooms with either *irresponsive EL↑-DA↑* or *irresponsive EL↓-DA↓* use). It should be noted here that the combined group *responsive OR responsive ±1* was used in specific statistical tests with the aim to evaluate whether it is usual for EL and DA to be strongly associated across rooms of specific groups (e.g. kitchens, North-facing rooms, ages (30– 39) etc.), in particular negatively associated. Type *responsive ±2* was not included in this combined group, even though it too refers to a negative association between EL and DA. The reason is that it refers to a weaker association (Table 1). In essence, testing for a significant frequency of *responsive OR responsive ±1* rooms in a group yields more statistical power for the analysis with respect to the EL and DA association effect, in comparison with testing for the frequency of *responsive OR responsive ±1 OR responsive ±2* rooms.

2.6. Data analysis

2.6.1. Association between EL and DA

The Spearman rank correlation coefficient r_S was used to measure the strength of association between EL and DA. The choice over Pearson's correlation was made since r_S is preferable in heavy-tailed distributions or when outliers are present (de Winter et al. 2016), which was the case with multiple room groups in this study. The association strength was interpreted according to the three-tier effect size categorization suggested by Cohen (Cohen 1988), where the effect size is considered small for an absolute value of r_S lower than 0.3, medium for an absolute value of r_S between 0.3 and 0.5, and large for an absolute value of r_S greater than 0.5. Post-hoc analysis using G*Power (Faul et al. 2007) revealed that the sizes of all groups and corresponding effect sizes r_S ensured the conventional statistical power threshold of 0.8 for a significance level $p < .05$.

2.6.2. Difference between associations

Pairwise comparisons between group correlation coefficients (r_{S1} vs r_{S2}) were performed, to evaluate whether the EL and DA association is stronger in certain room groups. The procedure involved constructing the 95% confidence interval for the r_S difference between a given pair of groups. The confidence interval construction approach can reveal both the precision and magnitude of an effect, as opposed to significance testing using a-priori hypotheses, which is why it is preferred over typical significance tests in the context of correlations (Olkin and Finn 1995). For a given pair of groups 1 and 2 with correlation coefficients r_{S1} and r_{S2}, the procedure included constructing the confidence interval for the $r_{S1} - r_{S2}$ difference (CI_{1_2}: [L, U]) according to Zou (2007). The difference between r_{S1} and r_{S2} was not considered statistically significant if CI_{1_2} contained zero. Zou (2007) provides different formulae to calculate CI_{1_2} for independent and dependent (paired) groups; the suitable calculation was used depending on the groups compared. In the case of orientation groups N, W, S, E, and balcony groups YES, NO, the pairs of groups (e.g. S vs E, or YES vs NO) were only partially paired, i.e. one portion of participants was included in both groups, and one portion of participants was included in only one of the two groups (either one). In these cases, responses were removed from the largest group randomly (with equal probability of removal), with the intent to acquire two independent groups with the highest possible size for the smaller group. Subsequently, the confidence interval for the $r_{S1} - r_{S2}$ difference was constructed according to the formulae suitable for independent groups.

2.6.3. Analysis of electric lighting use types

The percentage of rooms with a specific type of electric lighting use was calculated in each group. To compare percentages, one variable with two categories (1, 0) was created per type of use, where 1 indicates that the room is characterized by the type and 0 that it is characterized by any other type. Binomial tests (Glass and Hopkins 1995) were performed to assess if the percentage was significantly higher or lower than the percentage expected from random responses. If the EL and DA responses were randomly selected by each participant, the probability of occurrence for a given type would depend on the number of combinations shown in Table 1 (*responsive*: 7/49 = 0.14, *responsive ±1*: 8/49 = 0.16, *responsive ±2*: 4/49 = 0.08, *irresponsive EL↑-DA↑*: 15/49 = 0.31 and *irresponsive EL↓-DA↓*: 15/49 = 0.31). Similarly, for *responsive OR responsive ±1* the expected probability would be equal to (7 + 8)/49 = 0.31. Binomial tests where used to assess the statistical significance of deviations from these expected distributions (e.g. expected distribution for *responsive* use is 14% for 1, and 86% for 0). A significant test result indicated that the percentage of rooms with a given type of use was significantly high or low. The alpha level considered was $\alpha = 0.05$ (2-tailed).

Two different tests were used to compare groups, depending on group relation. McNemar tests were used for paired groups, namely the function groups (K, L, B), and Chi-square tests were used to compare independent groups, which included all other groups. The McNemar test can be used to compare percentages (e.g. percentages of *responsive* rooms) for two paired groups (e.g. KvL), and is suitable for non-parametric binary data (McNemar 1947). The test is applied to a 2 × 2 contingency table and is calculated based only on the number of subjects who gave different responses per group (discordant pairs of responses), for instance, a discordant pair of responses from the same subject could be: 'K: *responsive* = 0, L: *responsive* = 1′. Subjects that gave the same response for both groups (concordant pairs) are not accounted for by the test. The probability (*p*-value) of the test is based on discordant pairs, and the way it is calculated depends on their number. The test statistic has a chi-square distribution, but if the number of discordant pairs is less than 25, the statistic is better approximated by the binomial distribution. Previous research supports that this renders the test more conservative, and that a mid-*p* value (calculated *p*-value divided by 2) should be used in such cases (Fagerland et al. 2013); the mid-*p* value was used in this study wherever applicable as per the aforementioned suggestion. Finally, the Odds ratio (OR) was calculated to assess the effect size of the test (Cleophas and Zwinderman 2016), since the McNemar test only assesses significance.

The Chi-square test of independence was used to compare age, orientation and balcony groups. Specifically for this test, the six age groups were merged into two groups, one for all participants aged below 50 (< 50) and one for those aged 50 or higher (≥ 50). The Chi-square test of independence is designed to analyze group differences (e.g. South-facing vs North-facing rooms) when the dependent variable is measured at the nominal level (e.g. *responsive* = 1 or 0). It is robust with respect to the distribution of the data, i.e. it does not require equal variances among groups or homoscedasticity. As with McNemar's test, it is also applied on a contingency table, in this study a 2 × 2 table. In cases where at least one table cell has an expected count less than 5, Fischer's exact test can be used to compute the Chi-square test's probability (Fisher 1922). The test only assesses the significance of the group difference, thus it should be followed by a strength statistic (McHugh 2013). The strength statistic used was Cramer's V (Elliot et al. 2016), which ranges from 0, if the groups are independent of the variable, to 1, if the groups are perfectly predictive of the variable value, e.g. if room function is predictive of percentage of *responsive* rooms. According to Cohen (1988), Cramer's V for a 2 × 2 contingency table corresponds to a weak, medium or large effect when equal to 0.1, 0.3 or 0.5 respectively.

2.6.4. Analysis of PR responses

The proportion of PR responses (responses for a preferred underlit room, if there had to be one) was calculated per category, namely for categories "kitchen", "living room", "bedroom" and "I don't know which one" (Fig. 4). A Chi-square goodness-of-fit test was performed to evaluate if the categories were equally distributed (25% of responses per category), followed by Binomial tests per category to evaluate which one had a proportion significantly higher or lower than 25%. In addition, for those participants that age data were available (n = 76), binomial tests were performed to test the same assumption in each age group, i.e. which category of the PR response had a significantly different proportion than 25%, within different age groups.

3. Results

3.1. Association between EL and DA responses

The Spearman rank correlation between EL and DA responses for different groups is shown in Table 2. There is a significant negative association ($p < .05$) for all groups. Overall, the size of the association is large (All rooms: $r_S = -0.588$, $p < .01$), and ranges from medium-to-large to large across different groups ($-0.4 \le r_S \le -0.8$). The association was not significantly different between room functions as per the confidence interval of the r_S difference (CI_{K_L}: [−0.14, 0.24], CI_{K_B}: [−0.24, 0.16], CI_{L_B}: [−0.27, 0.09], $p < .01$). With respect to age groups, the strongest associations were found for groups "< 30", "(40– 49)" and "≥ 70" (r_S = 0.-0.772, −0.767 and −0.746 respectively). All three were significantly higher than the association in the (50– 59) age group, but the confidence intervals of r_S differences were wide ($CI_{<30\_50\text{-}60}$: [−0.66, −0.03], $CI_{40\text{-}50\_50\text{-}60}$: [−0.65, −0.06], $CI_{\ge 70\_50\text{-}60}$: [−0.63, −0.06]). When comparing between younger (age < 50) and older (age ≥ 50) participants, no significant difference was found. With respect to orientation, the North and South-facing rooms exhibit a medium-to-large effect (N: $r_S = -0.405$, S: $r_S = -0.395$, $p < .05$), while West and East-facing rooms exhibit a large and more significant effect (W: $r_S = -0.582$, E: $r_S = -0.726$, $p < .01$). Significant differences between associations were identified between East and North (CI_{E_N}: [−0.66, −0.04]) and between East and South (CI_{E_S}: [−0.65, −0.05]). In other words, the association between EL and DA was significantly higher in East-facing rooms compared to North and South-facing rooms ($p < .05$). Finally, the association is strong both for rooms with and without a balcony obstruction (YES: $r_S = -0.576$, NO: $r_S = -0.550$, $p < .01$), without a significant difference between the two groups (CI_{YES_NO} [−0.33, 0.20]).

The effect of geometric attributes on r_S was evaluated separately in each function group K, L, B, since paired samples t-tests indicated that these attributes differ significantly between groups ($p < .05$). Table 3 shows the association for different ranges of attributes and different orientations. Cases where r_S was significantly different between two groups are marked with "*". It is shown that there is a negative

Table 2. Spearman rank correlation coefficient r_S for overall sample S_{ALL} (n = 225), and for groups according to function, age, orientation and balcony obstruction.

Variable	Group	n	r_S
All rooms	S_{ALL}	225	−0.588**
Function	K	75	−0.570**
	L	75	−0.617**
	B	75	−0.531**
Age	< 30	21	−0.772**
	(30– 39)	45	−0.478**
	(40– 49)	30	−0.767**
	(50– 59)	48	−0.408**
	(60– 69)	33	−0.633**
	≥ 70	42	−0.746**
Orientation	N	35	−0.405*
	W	85	−0.582**
	S	38	−0.395*
	E	67	−0.726**
Balcony[a]	NO	155	−0.550**
	YES	41	−0.576**

**, ** significance p < .05, p < .01 respectively*

[a]*only includes single-aspect rooms*

Table 3. Spearman rank correlation coefficient r_S per room function, within different ranges of GFR, GWR, $GW_{INT}R$, and different orientations.

	Kitchen			Living room			Bedroom		
Variable	Group	n	r_S	Group	n	r_S	Group	n	r_S
GFR	(0– 9.81)	37	−0.513**	⋆(0– 13.79)	34	−0.443**	(0– 10.9)	39	−0.540**
	(9.82– 15.4)	38	−0.623**	⋆(13.8– 25.3)	41	−0.754**	(11.0– 24.6)	36	−0.528**
GWR	(0– 14.69)	36	−0.547**	(0– 16.99)	36	−0.564**	(0– 13.99)	36	−0.633**
	(14.7– 27.7)	39	−0.618**	(17– 32)	39	−0.613**	(14– 33.9)	39	−0.429**
$GW_{INT}R$	(0– 3.4)	34	−0.618**	⋆(0– 6.69)	35	−0.436**	(0– 3.79)	37	−0.542**
	(3.5– 4.3)	41	−0.529**	⋆(6.7– 13.2)	40	−0.773**	(3.8– 10.1)	38	−0.529**
Orientation	N	5	−0.649	N	13	−0.318	N	18	−0.402
	W	29	−0.623**	W	32	−0.714**	W	23	−0.166
	S	13	−0.088	S	12	−0.405	S	13	−0.625*
	E	28	−0.675**	E	18	−0.644**	E	21	−0.804**

**, ** significance $p < .05$, $p < .01$ respectively*

⋆ *significant difference between two correlations*

association ($p < .05$) for the majority of groups. Wherever significant, the association effect ranges between −0.429 and −0.804. This indicates that the stratification of rooms based on function and geometry did not yield different results compared to Table 2. In the case of living rooms, two geometric attributes yield a markedly different association depending on their range. The association is significantly stronger for living rooms with higher GFR ($r_{S\_13.8–25.3} = −0.754$) compared to lower GFR ($r_{S\_0-13.8} = −0.443$), $CI_{0-13.8\_13.8–25.3}$: [0.02, 0.65], and for living rooms with higher GW_{INT} R ($r_{S\_6.7–13.2} = −0.773$) compared to lower GW_{INT} R ($r_{S\_0-6.7} = −0.436$), $CI_{0-6.7\_6.7–13.2}$: [0.05, 0.67]. In essence, the lower range geometry values correspond to single-aspect living rooms, while the higher range values correspond to multi-aspect living rooms. It should be noted that age, orientation and balcony categories were equally represented among these pairs of groups. Finally, with respect to orientation, the association is strong in kitchens and living rooms oriented toward East or West ($0.623 \le |r_S| \le 0.714$, $p < .01$), and in bedrooms oriented toward East or South (East: $r_S = −0.804$, $p < .01$, South: $r_S = −0.625$, $p < .05$). However, post-hoc analysis indicated that there is no statistical power for r_S in the rest of the groups, i.e. the possibility that there is an association between EL and DA cannot be ruled out for them.

3.2. Type of electric lighting use

Table 4 shows the percentage of rooms in each group that have *responsive, responsive ± 1, responsive ± 2, responsive OR responsive ± 1, irresponsive EL↑-DA↑* or *irresponsive EL↓-DA↓* lighting use. Markers (+) and (-) indicate that a percentage is significantly higher or lower than what would be expected from random responses (Binomial test). The first row of the table confirms that there is an association between EL and DA. For the overall sample (All rooms), the percentage of rooms with either a perfect or a nearly perfect negative association between EL and DA (column *responsive OR responsive ±1*) is 73%. The percentage was found significantly higher (+) than what would be expected from random responses (15%). Rooms characterized by *responsive, responsive ± 1* and *responsive ± 2* correspond to 38%, 36% and 6% of the overall sample (respectively). The percentages of rooms with *irresponsive EL↑-DA↑* and *irresponsive EL↓-DA↓* electric lighting use were found significantly low (All rooms, *irresponsive EL↑-DA↑*: 10%, *irresponsive EL↓-DA↓*: 10%, (-)).

Observing Table 4, it is shown that the percentage of *responsive OR responsive ± 1* is significantly high across all groups (all percentages (+)). In addition, for the majority of groups, there were significantly few rooms with *irresponsive EL↑-DA↑* or *irresponsive EL↓-DA↓* use (most percentages (-)). Exceptions for *irresponsive EL↑-DA↑* use include the two lower age groups (<30: 24%, (30– 39): 20%), and South-facing rooms (S: 18%). Exceptions for *irresponsive EL↓-DA↓* use include age groups (50– 59) and ≥70 (*irresponsive EL↓-DA↓*: 17% and 14% respectively), as well as North-facing and South-facing rooms (*irresponsive EL↓-DA↓*: 17% and 13% respectively). Overall, frequent *responsive OR responsive±1* use persists across groups of different characteristics. The percentage of *irresponsive EL↑-DA↑* rooms are significantly low for

Table 4. Percentage of rooms per group with a given electric lighting use type. Markers (+) and (-) indicate that a percentage is significantly higher or lower (respectively) than what was expected (Binomial test).

Variable	Group	n	responsive (%)	responsive ±1 (%)	responsive ±2 (%)	responsive OR responsive ±1 (%)	irresponsive EL↑-DA↑ (%)	irresponsive EL↓-DA↓ (%)
All rooms	S_{ALL}	225	38 (+)	36 (+)	6	73 (+)	10 (-)	10 (-)
Function	K	75	29 (+)	36 (+)	8	65 (+)	16 (-)	11 (-)
	L	75	48 (+)	32 (+)	5	80 (+)	5 (-)	8 (-)
	B	75	36 (+)	39 (+)	5	75 (+)	9 (-)	9 (-)
Age	< 30	21	48 (+)	24	5	71 (+)	24	0 (-)
	(30– 39)	45	20	47 (+)	2	67 (+)	20	11 (-)
	(40– 49)	30	40 (+)	47 (+)	0	87 (+)	10 (-)	3 (-)
	(50– 59)	48	35 (+)	27	8	62 (+)	13 (-)	17
	(60– 69)	33	42 (+)	36 (+)	18	79 (+)	0 (-)	3 (-)
	≥ 70	42	48 (+)	33 (+)	5	81 (+)	0 (-)	14
Orientation	N	35	36 (+)	28 (+)	8	64 (+)	11 (-)	17
	W	85	43 (+)	39 (+)	4	82 (+)	7 (-)	7 (-)
	S	38	32 (+)	34 (+)	3	66 (+)	18	13
	E	67	36 (+)	36 (+)	10	72 (+)	9 (-)	9 (-)
Balcony[a]	NO	155	38 (+)	35 (+)	5	73 (+)	11 (-)	12 (-)
	YES	41	29	41 (+)	12	71 (+)	10 (-)	7 (-)

(+), (-) significantly higher or lower than expected (Binomial test).

[a] *only includes singe-aspect rooms*

all groups, while the percentage of *irresponsive EL↓-DA↓* rooms are significantly low for most groups (in 11 out of 15 groups).

With respect to differences between groups K, L, B, the McNemar test result was statistically significant in three cases, all of which correspond to the comparison between K and L. The percentages of *responsive* and *responsive OR responsive ±1* were significantly higher in living rooms compared to kitchens (*responsive:* $p = .003$, OR = 3.8, *responsive OR responsive ±1:* $p = .017$, OR = 2.83), and the percentage of *irresponsive EL↑-DA↑* rooms was significantly higher in kitchens compared to living rooms (*irresponsive EL↑-DA↑:* $p = .019$, OR = 5.0). There were no other significant differences between function groups. With respect to age group comparisons, the Chi-square tests revealed one significant difference. Participants aged 50 or higher reported *irresponsive EL↑-DA↑* use significantly less frequently than participants aged below 50 ($\chi^2(1) = 9.443$, $p = .002$), but the magnitude of the difference was weak-to-medium (Cramer's V = 0.21, $p < .01$). With respect to orientation group comparisons, the Chi-square tests revealed two significant differences, both regarding *responsive OR responsive ±1* use. This type of use was reported more frequently in West-facing rooms compared to North-facing rooms (x2(1) = 5.896, p =.015), with a weak-to-medium effect size (Cramer's V = 0.227, $p = .015$), and more frequently in West-facing rooms compared to South-facing rooms (x2(1) = 4.055, p =.044), with a weak-to-medium effect size (Cramer's V = 0.391, $p = .026$). Finally, no significant differences were identified between balcony groups NO, YES for any type of use.

Each pie chart in Fig. 5 corresponds to a subgroup including rooms of a specific function (kitchen, living room or bedroom) oriented toward a particular orientation (N, W, S, E). Each slice corresponds to the percentage of rooms in the subgroup that are characterized by a given type of electric lighting use (*responsive, responsive ±1*, etc.). Cumulative percentages are shown below each pie chart for *responsive OR responsive ± 1* rooms (green hues) and *irresponsive EL↑-DA↑ OR irresponsive EL↓-DA↓* rooms (red hues), which correspond to proportions of rooms with a negative and positive association between EL and DA respectively (green hues: negative, red hues: positive). It is shown that the green hue prevails, i.e. lighting use is *responsive OR responsive ± 1* for the majority of rooms in each subgroup (> 50% of rooms). Binomial tests indicated that the proportion of *responsive OR responsive ± 1* rooms is significantly higher than 50% in i) West-facing kitchens (90%, $p < .01$), ii) West and East-facing living rooms (91%, $p < .01$ and 72%, $p < .05$ respectively) and in iii) West and East-facing bedrooms (74%, $p < .05$ and 95%, $p < .01$ respectively). Comparing orientations for each room function, one significant difference was revealed. West-facing kitchens reported *responsive OR responsive ± 1* use more frequently compared to East-facing

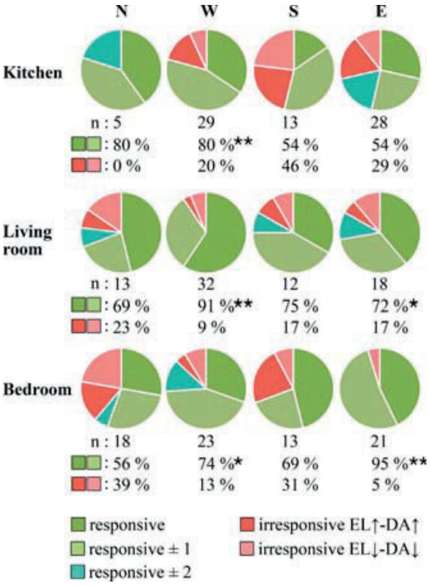


Fig. 5. Proportion of each type of electric lighting use per orientation and room function. Cumulative percentages are shown for *responsive OR responsive ± 1* rooms (green hues), and for *irresponsive EL↑-DA↑ OR irresponsive EL↓-DA↓* rooms (red hues). The number of rooms per function and orientation is indicated by "n". Markers "*" and "**" indicate significance at 0.05 and 0.01 respectively, for Binomial tests with an expected proportion of 50%.

kitchens ($\chi^2(1) = 4.247, p = .039$), with a medium effect size (Cramer's V = 0.273, $p < .05$). Two more comparisons had marginally significant results ($p < .1$). Living rooms oriented toward West reported *responsive OR responsive ± 1* use more frequently than living rooms oriented toward East ($\chi^2(1) = 3.075, p = .091$, Cramer's V = 0.273, $p = .079$), and bedrooms oriented toward East reported *responsive OR responsive ± 1* use more frequently than bedrooms oriented toward West ($\chi^2(1) = 3.731, p = .062$, Cramer's V = 0.291, $p = .053$). This information indicates that West orientation is favorable for kitchens and living rooms, while East is favorable for bedrooms, which is in line with the r_S magnitude shown in Table 3 for the orientation groups; however, larger room samples are required to corroborate this finding.

3.3. Daylight prioritization per room function

Figure 6 shows the percentage of responses in each PR category for a sample of 108 participants. These are responses to the question *"If any of the rooms would be without daylight, which one would you choose?"*. Percentages that correspond to significant Binomial test results are marked with "*". It is shown that the bedroom is the space where most occupants would tolerate low daylight levels, if they had to choose one such room (62.0% of the occupants). The second most chosen category, and more frequent than the remaining two choices, is the "I don't know which one" category (25.0%). The "Living room" responses were few (8.3%), and "Kitchen" responses were extremely few (4.6%). This indicates that the kitchen is the space within the apartment where the vast majority of participants would not tolerate the lack of daylight (only 5 out of 108 chose "Kitchen"). The Chi-square goodness of fit test for an expected percentage of 25% per category was significant, $\chi^2(3) = 89.19$, $p < .01$. The result was followed by individual Binomial tests per category. It appeared that the percentages of "Kitchen" and "Living room" responses were significantly lower than 25% (Kitchen: 4.6%, Living room: 8.3%, $p < .01$ for both), and the percentage of "Bedroom" responses was significantly higher (62.0%, $p < .01$). The percentage of participants who chose category "I don't know which one" was exactly 25% (27 out of 108 responses).

Figure 7 shows the percentage of PR responses that correspond to each room function, per age group. Percentages that are significantly higher or

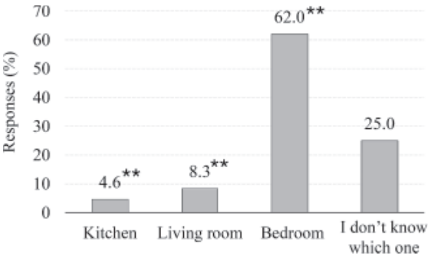


Fig. 6. Percentage of PR responses per category. The PR responses were given for the question: "If any of the rooms would be without daylight, which one would you choose" (Fig. 4). Indicated with "**" are percentages significantly higher or lower than 25%, as per the Binomial test results.

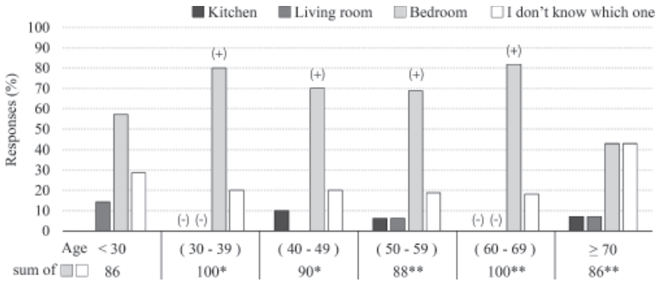


Fig. 7. Percentage of PR responses per room function and age group. Significantly high or low percentages are marked with (+) or (-) respectively. The x-axis also shows the cumulative percentage of responses "Bedroom" or "I don't know which one". The percentages are marked with "*" and "**" when significantly higher than 50%, as per the Chi-square goodness-of-fit test (p < .05, p < .01 respectively).

lower than 25% (as per the Binomial tests ($p < .05$)), are marked with "(+)" and "(-)". The numerals below the age ranges at the x-axis show the percentage of responses that were either "Bedroom" or "I don't know which one", i.e. the percentage of participants that did not choose neither the "Kitchen" nor the "Living room" category. These percentages are marked with "*" and "**" when significantly higher than 50%, as per the Chi-square goodness-of-fit test ($p < .05$, $p < .01$ respectively). It is shown that the "Bedroom" category was chosen most frequently and the "I don't know which one" was the second most chosen category, in all groups except for the "≥ 70" group where the two categories have the same proportion (43% each). This is the only group where the majority of participants did not choose "Bedroom". For this group, the "Bedroom" percentage (43%) is not significantly higher than 25%, which is the expected percentage if all categories where considered equally probable. For the rest of the groups, the "Bedroom" response is significantly more frequent than 25%. Overall, the percentage of participants who did not choose neither "Kitchen" nor "Living room" deviated significantly from 50%, as indicated consistently by the percentages shown below the x-axis ("Bedroom" OR "I don't know which one" percentages between 86% and 100%). A significant result was not obtained for the "< 30" group due to low group size (n = 7).

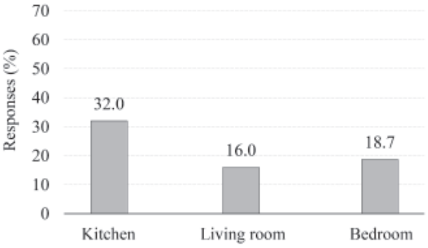


Fig. 8. Percentage of high-frequency electric lighting use (EL ≥ 5) responses, per room function.

Figures 8 and 9 juxtaposed with Fig. 6 can help illustrate a contradiction between reported electric lighting use and perceived daylit area on one hand (EL & DA), and preferences with respect to daylight availability on the other hand (PR). Figure 8 suggests that daytime electric lighting use is more frequent in kitchens, as nearly one out of three kitchens uses electric lighting more often than half the daylight hours in a year (EL ≥ 5 in 32% of the rooms). McNemar tests indicated that the percentage of kitchens was significantly higher than that of living rooms (p = .004, OR = 5) and significantly higher than that of bedrooms (p = .021, OR = 3). In addition, Fig. 9 shows that kitchens were reported underlit (DA ≤ 3) more often than the other two room functions. In particular, nearly one out of four occupants reported a low daylit area in their kitchen (DA ≤ 3, K: 24%), while the corresponding percentages for living rooms and bedrooms were 14.7% and 16.0% respectively. The McNemar test result was marginally

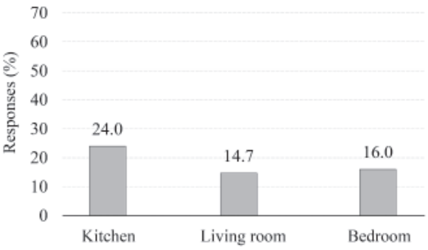


Fig. 9. Percentage of low daylit area responses (DA ≤ 3) per room function.

significant when comparing kitchens with living rooms (p = .059) and kitchens with bedrooms (p = .09). Interpreting the information provided by Figs. 6, 8 and 9 combined, we can infer that there is a need to ensure/improve daylight provision for kitchens. The latter is true since: i) very few occupants would tolerate an underlit kitchen (Fig. 6), the most frequent electric lighting use during daytime occurs in kitchens (Fig. 8) and iii) kitchens were most frequently reported as underlit (Fig. 9).

4. Discussion

Reducing unnecessary electricity for lighting in the residential sector by means of daylight utilization is a laudable goal. As stated in the Introduction section, an increase of remote work (work-from-home) could induce an increase in residential electricity used for lighting; however, the net difference in electricity use would depend on the lighting power density [W/m2] of offices (where people left from) compared to residences (where people went to). The case might be that residences use less artificial lighting per unit area compared to offices, which would then result in less electricity use overall if people work from home. On the other hand, the lighting load per person should be factored in this comparison, as employees may share ambient lighting in e.g. open offices, while each employee would use a different luminaire if they worked from their individual home environment. Whatever the case, improving daylight performance to reduce electricity use for lighting in residences is a laudable goal, as it increases the resilience of these spaces and renders them more efficient as potential working spaces, if the need arises.

Daylight utilization in residences is also in phase with the need for integrative lighting (CIE 2016), which may produce both physiological and psychological benefits for humans. Although there are still gaps of knowledge regarding these benefits (Münch et al. 2020), there is evidence that timing the exposure to daylight radiation and increasing its quantity are very important (Figueiro 2017), and this is relevant specifically for residences. The reason is that residences are where people sleep, which makes their need for daylight in these spaces to vary with time: they require light with high melanopic content upon waking up and during the day, light with lower melanopic content before going to bed, and darkness when they sleep. This warrants the importance of daylight design for residences with respect to timing illumination for different rooms.

With respect to lighting use types, there are two considerations pertaining to their definition. Type *irresponsive EL↑-DA↑* was assumed for rooms with frequent electric lighting use despite a large daylit area (EL, DA responses ≥ 4, excluding the 4v4 pair). The case could be that this type does not necessarily characterize an occupant who uses electric lighting regardless of daylight conditions. In cases of deep rooms, an occupant may use electric lighting at the back end of the room if the task is located there, although most of the room area may be adequately daylit. It appeared that there was only one living room with *irresponsive EL↑-DA↑* use and designed with extensive depth (7.5 m), where a task could potentially be conducted in a dark location while most of the room area remains daylit. The most *irresponsive EL↑-DA↑* rooms were kitchens (Table 4). Kitchens with *irresponsive EL↑-DA↑* use had their counter on the side wall, the counter stretching throughout the room depth (4.5– 4.8 m). This depth was within the recommended range for daylit spaces (Reinhart 2005), and indeed these rooms were reported as having an extended daylit area (DA ≥ 5). In kitchens though, tasks of high contrast and small size such as cooking require higher levels of illuminance (DiLaura et al. 2011), probably higher than what would be perceived as adequate for the overall room area, which explains the higher percentage of *irresponsive EL↑-DA↑* use in kitchens. The same spatial consideration applies for *irresponsive EL↓-DA↓* electric lighting use. A person could potentially live in a room considered dark (DA ≤ 3), but still use electric lighting only on rare occasions (EL ≤ 3), e.g. if the task is located next to the window. Checking the apartment plans and survey photographs verified that this was not possible in kitchens or bedrooms. However, it could be possible in living rooms with a sitting area next to the window and the rest of the area stretching deep into the building core. This was possible in five out of six *irresponsive EL↓-DA↓* living rooms, which indicates that the term *irresponsive EL↓-DA↓* did not necessarily pertain to behavior characterized by indifference toward daylight conditions. If the latter is true, then these rooms could be considered similar to the rooms were EL and DA were negatively associated, further verifying the hypothesis of this study.

With respect to occupant preferences, it was shown that the majority of respondents (62%) would choose the bedroom as the underlit room of their apartment, if they had to choose one such room. This finding provides knowledge suitable for design guidelines. For instance, if one room or a percentage of the apartment area is predestined to be darker due to uncontrolled factors (e.g. high preexisting surrounding obstructions), it is preferable to accommodate a bedroom function in that space instead of a kitchen function. However, this prioritization should not affect children, which may be present in their bedroom earlier in the afternoon compared to their parents (Wolf 2020; Wolf et al. 2019). Daylight provision should also be considered in bedrooms for elderly people, as the "Bedroom" response did not stand out significantly in the "≥ 70" age group (Fig. 7). On the other hand, the kitchen was selected by a remarkably low amount of respondents (5 out of 108 respondents). Results indicated that this room function: i) would not be tolerated underlit, ii) was reported most often as using electric lighting frequently (EL ≥ 5) and iii) was reported most often as having a small daylit area (DA ≤ 3). It can therefore be inferred that daylight provision is needed for kitchens. The author has previously received skepticism for this conclusion, when presenting preliminary results in previous symposia or workshops, including comments from practitioners of architecture and policy makers in Sweden. The main point raised was that there is more necessity for daylight where one dines, compared to where one cooks, concluding that no daylight provision is necessary for the kitchen. Although this sounds like a reasonable argument, it is not supported by scientific evidence. The participants of this study were asked to exclude the dining area when responding for the kitchen, and still reported that they would not tolerate low daylight levels. This finding is in agreement with recently published work conducted in 45 Swedish apartments, where the kitchen was chosen as *the most important room to have access to a lot of daylight*, even though a choice was given to select the dining room instead (Eriksson et al. 2019, 21). In particular, the dining room only ranked third out of four room functions in terms of daylight prioritization, the kitchen being the most important, followed closely only by the living room, similarly what was found here (Fig. 6). The bedroom was voted as the least important room by a high margin, also similarly to the results presented here.

5. Conclusions

This paper presented results of a questionnaire survey in 75 apartments located in typical residential buildings in Malmö, Sweden, comprising 225 rooms that included kitchens, living rooms and bedrooms. The aim of the study was to assess if there is a potential to reduce residential electric lighting use by exploiting daylight, and to assess which rooms are prioritized with respect to daylight admission. The following may be concluded:

5.1. Associations between electric lighting use and daylit area

Overall, the size of the association between self-reported frequency of electric lighting use (EL) and perceived daylit area (DA) was found strong ($r_S = -0.588$, $p < .01$). The association was persistent through groups defined according to function, occupant age, orientation, balcony obstruction and fenestration size, and ranged between −0.4 and −0.8. There were no significant differences between different age groups. Neither between room functions, with the sole exception of living rooms: higher fenestration with respect to floor area (GFR) or internal wall area ($GW_{INT}R$) resulted in a higher association between EL and DA in living rooms ($p < .05$). With respect to orientation, East and West exhibited a large association effect ($p < .01$), with East inducing a significantly higher association compared to North and South. Finally, there was no significant difference between rooms with and without a balcony obstruction.

5.2. Type of electric lighting use

The majority of rooms was characterized by either *responsive* or *responsive ±1* electric lighting use (73% of rooms). The corresponding percentage for individual groups based on function, age, orientation or balcony obstruction ranged from 62% to 87%. The percentage of rooms with *irresponsive EL↑-DA↑* or *irresponsive EL↓-DA↓* use was significantly low (*irresponsive EL↑-DA↑*: 10%, *irresponsive EL↓-DA↓*: 10%, $p < .05$). Kitchens were characterized less often by *responsive OR responsive ±1* use and more often by *irresponsive EL↑-DA↑* use, compared to living rooms ($p < .05$). With respect to occupant age, it was shown that younger people (age < 50) reported significantly higher *irresponsive EL↑-DA↑* use compared to older people (age ≥ 50), but the magnitude of the difference was relatively weak (Cramer's V = 0.21, $p < .01$). Regarding orientation, the optimum choice with respect to *responsive OR responsive ±1* use was associated with room function. West induced a higher amount of *responsive OR responsive ±1* rooms for kitchens and living rooms ($p = .039$, $p = .091$ respectively), while East induced a higher amount for bedrooms ($p = .062$).

5.3. Occupant preferences

With respect to occupant preferences, a significantly high amount of respondents would choose the bedroom as the underlit room of their apartment, if they had to choose one such room (62%, $p < .05$). The occupants who chose the kitchen or the living room were significantly fewer than what would be expected from random responses (kitchen: 4.6%, living room: 8.3%, $p < .05$). The same pattern was observed within each age group, except for the group with the oldest participants (age ≥ 70); responses "Bedroom" and "I don't know which one" were equally represented in this group (25% each), implying that perhaps older people spend more time in their bedroom, compared to other ages. This differentiation notwithstanding, all age groups gave very few "Kitchen" or "Living room" responses, indicating that these two room functions are the most prioritized in terms of daylight availability regardless of age, which is in agreement with previous work (Eriksson et al. 2019). In particular, the percentage of occupants that selected the kitchen was extremely low (4.6%), corresponding to 5 out of 108 participants. The latter contradicts the occupants' experience, since kitchens were reported most often as having i) more frequent electric lighting use compared to other rooms (EL ≥ 5, K: 32.0%, L: 16.0%, B: 18.7%) and ii) a smaller daylit area (DA ≤ 3, K: 24%, L: 14.7%, B: 16.0%). The study indicates that daylight provision is necessary for this room function, if electric lighting use is to be reduced and occupant preferences to be accounted for.

5.4. Applications

The knowledge provided could contribute to policymaking or design guidelines, if considered when formulating daylight performance criteria for residential spaces. Although there were no photometric measurements carried out, with which to correlate subjective responses, the results may be used to define a suitable timeframe for evaluations, or to make distinctions between room types. For instance, the stronger associations for East and West-facing rooms warrant that morning and afternoon hours constitute the most important time-period for residences. This is in agreement with residential occupancy profiles (Barthelmes et al. 2018; Mitra et al. 2020; Wolf et al. 2019). Differences between room functions may also be considered. The fact that the optimum orientation varies according to function (Kitchen, Living room: West, Bedroom: East) implies that different hours of the day could be considered for the evaluation of different rooms. Finally, the results indicate that different criteria thresholds may be stipulated per room function, as occupants were shown to prioritize kitchens and living rooms over bedrooms.

Acknowledgments

The author is indebted to all participating residents whose responses were crucial for this research. The housing companies (MKB, HSB, Stena Fastigheter and Riksbyggen) are also acknowledged for allowing this work to take place within their properties, and for providing access to the apartments for on-site measurements. Marie-Claude Dubois and Henrik Davidsson are acknowledged for the necessary communications with tenants. Thorbjörn Laike is acknowledged for his valuable comments regarding the structure of the questionnaire. The author would also like to thank Ioannis-Antonios Moutsatsos and Danai Vogiatzi for reviewing this work. Special thanks to Marwan Abugabbara and Ludvig Haav for undertaking the Arabic and English translation of the questionnaire respectively.

Disclosure statement

The author has no financial interests to declare.

Funding

This work was funded by the Swedish Energy Agency (Energimyndigheten, grant nr 41816-2), Arkus (Stiftelsen Arkus) and ARQ (c/o White Architects AB), grant nr 12:2016).

ORCID

Iason Bournas http://orcid.org/0000-0003-4535-4235

References

Arendt J, Middleton B. 2018. Human seasonal and circadian studies in Antarctica (Halley, 75°S). General and Comparative Endocrinology. 258: 250–258. doi:10.1016/j.ygcen.2017.05.010

Barthelmes VM, Li R, Andersen RK, Bahnfleth W, Corgnati SP, Rode C. 2018. Profiling occupant behaviour in Danish dwellings using time use survey data. Energy and Buildings. 177: 329–340. doi:10.1016/j.enbuild.2018.07.044

Beauchemin KM, Hays P. 1998. Dying in the dark: sunshine, gender and outcomes in myocardial infarction. Journal of the Royal Society of Medicine. 91(7): 352–354. doi:10.1177/014107689809100703

BOVERKET. 2020a. Mandatory provisions and general recommendations BFS 2011:6 with amendments up to BFS 2018:4. Karlskrona (Sweden): The Swedish National Board of Housing, Building and Planning

BOVERKET. (2020b). The Swedish National Board of Housing, Building and Planning. Dagsljus, solljus och belysning i byggnader [Daylight, sunlight and lighting in buildings]. Karlskrona (Sweden): BOVERKET, [accessed 2020 April 30]. https://www.boverket.se/sv/byggande/halsa-och-inomhusmiljo/ljussolljus/

Boyce PR. 2017. Human factors in lighting (3rd edition). London (UK): CRC Press, Taylor & Francis Group.

CEN. 2018. European Standard EN 17037:2018 Daylight in Buildings. Brussels (Belgium): European Committee for Standardization.

Christoffersen J, Johnsen K. 1999. Vinduer og dagslys - en feltundersøgelse i kontorbygninger (Windows and Daylight - a Post-occupancy Evaluation of Offices). SBI-rapport 318, 71 pages (in Danish). Retrieved from https://vbn.aau.dk/ws/portalfiles/portal/14365841/Rapport_318.pdf

CIE. 2016. International Lighting Vocabulary DIS 017/E:2016 ILV. Vienna (Austria): International Commision on Illumination.

Cleophas TJ, Zwinderman AH. 2016. Clinical Data Analysis on a Pocket Calculator. Understanding the Scientific Methods of Statistical Reasoning and Hypothesis Testing (2nd edition). Cham (Switzerland): Springer International Publishing.

Cohen J. 1988. Statistical power analysis for the behavioral sciences (2nd edition). New York (USA): Lawrence Erlbaum Associates.

Czeisler C, Gooley J. 2007. Sleep and circadian rhythms in humans. Cold Spring Harbor Symposia on Quantitative Biology. 72: 579–597. doi:10.1101/sqb.2007.72.064

de Winter JCF, Gosling SD, Potter J. 2016. Comparing the Pearson and Spearman correlation coefficients across distributions and sample sizes: A tutorial using simulations and empirical data. Psychological Methods. 21(3): 273–290. doi:10.1037/met0000079 & 10.1037/met0000079.supp (Supplemental)

DiLaura DL, Houser KW, Mistrick RG, Steffy GR. 2011. The lighting handbook: reference and application (10th edition). New York (USA): Illuminating Engineering Society of North America.

El Kontar R, Rakha T. 2018. Profiling Occupancy Patterns to Calibrate Urban Building Energy Models (UBEMs) Using Measured Data Clustering. Technology | Architecture + Design. 2(2): 206–217. doi:10.1080/24751448.2018.1497369

Elliot M, Fairweather I, Olsen W, Pampaka M. 2016. Cramer's v. In: A Dictionary of Social Research Methods. Online version: Oxford University Press. 1st edition.

Eriksson S, Waldenström L, Tillberg M, Österbring M, Kalagasidis AS. 2019. Numerical simulations and empirical data for the evaluation of daylight factors in existing buildings in Sweden. Energies. 12(11):2200.

Fagerland MW, Lydersen S, Laake P. 2013. The McNemar test for binary matched-pairs data: mid-p and asymptotic are better than exact conditional. BMC Med Res Methodol. 13(1):1–8.

Faul F, Erdfelder E, Lang AG, Buchner A. 2007. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods. 39(2):175–191.

Figueiro MG. 2017. Disruption of circadian rhythms by light during day and night. Curr Sleep Med Rep. 3(2):76–84.

Fisher RA. 1922. On the interpretation of $\chi 2$ from contingency tables, and the calculation of P. J Royal Stat Soc. 85(1):87–94.

Fotios S. 2019. Using category rating to evaluate the lit environment: is a meaningful opinion captured? LEUKOS. 15 (2–3):127–142.

Glass GV, Hopkins KD. 1995. Statistical methods in education and psychology. 3rd ed. Boston (USA): Allyn and Bacon.

Godden DR, Baddeley AD. 1975. Context dependent memory in two natural environments: on land and underwater. British J Psychol. 66(3):325–331.

Goldstein EB. 2014. Cognitive psychology: connecting mind, research, and everyday experience. 4th ed. Stamford (USA): Cengage Learning.

Grasshopper. 2020. Version 1.0.0007 Seattle (WA): [software]. Seattle (WA): Robet McNeel & Associates.

GWA. 2020. Global workplace analytics. Latest work-at-home/telecommuting/mobile work/remote work statistics. San Diego (USA): GWA [accessed 2020 May 12]. https://globalworkplaceanalytics.com/telecommuting-statistics.

Hall T, Rörby M. 2009. Stockholm: The Making of a Metropolis. 1st ed. London (UK): Routledge.

Hardill I, Green A. 2003. Remote working—altering the spatial contours of work and home in the new economy. New Technol Work Employ. 18(3):212–222.

Hickman A, Saad L. 2020. Reviewing remote work in the U.S. under COVID-19. Online article. Washington(USA): Gallup [accessed 2020 May 10]. http://ludwig.lub.lu.se/login?url=https://search.ebscohost.com/login.aspx?direct=true&db=bth&AN=143431112&site=eds-live&scope=site

Houser KW, Tiller DK. 2003. Measuring the subjective response to interior lighting: paired comparisons and semantic differential scaling. Light Res Technol. 35(3):183–198.

Hu S, Yan D, An J, Guo S, Qian M. 2019. Investigation and analysis of Chinese residential building occupancy with large-scale questionnaire surveys. Energy Build. 193:289–304.

Johansson D, Bagge H, Lindstrii L. 2011, November 14–16. Measured occupancy levels in 18 Swedish apartment buildings - application to input data for building simulations. Paper presented at the 12th Conference of International Building Performance Simulation Association; Sydney (Australia).

Knoop M, Stefani O, Wirz-Justice A, Bueno B, Matusiak B, Hobday R, Martiny K, Kantermann T, Aarts MPJ, Zemmouri N, et al. 2019. Daylight: what makes the difference? Light Res Technol. 52(3):423–442.

Kyriacou CP, Hastings MH. 2010. Circadian clocks: genes, sleep, and cognition. Trends Cogn Sci. 14(6):259–267.

Lam WMC. 1986. Sunlighting as formgiver for architecture. 1st ed. New York (USA): Van Nostrand Reinhold.

Lietz P. 2010. Research into questionnaire design. Int J Market Res. 52(2):249–272.

Lobaccaro G, Savarino M, Goia F, Fabrizio E. 2019. Relation between daylight availability and electric lighting in a single-family house. Paper presented at the 1st Nordic conference on Zero Emission and Plus Energy Buildings; Trondheim (Norway).

Malmö-Stad. 2020. Stadsbyggnadskontorets arkiv [Municipal building archives]. Malmö (Sweden): Malmö Stad [accessed 2020 May 7]. https://malmo.se/Service/Bygga-och-bo/Stadsbyggnadskontorets-arkiv.html.

Mardaljevic J, Andersen M, Roy N, Christoffersen J. 2011. Daylighting metrics for residential buildings. Paper presented at the 27th Session of the CIE; Sun City (South Africa).

McHugh ML. 2013. The chi-square test of independence. Biochemia Medica. 23(2):143–149.

McNemar Q. 1947. Note on the sampling error of the difference between correlated proportions or percentages. Psychometrika. 12(2):153–157.

Mead MN. 2008. Benefits of sunlight: a bright spot for human health. Environ Health Perspect. 116(4):161–167.

Meade AW, Craig SB. 2012. Identifying careless responses in survey data. Psychol Methods. 17(3):437–455.

Menculini G, Verdolini N, Murru A, Pacchiarotti I, Volpe U, Cervino A, Steardo L, Moretti P, Vieta E, Tortorella A. 2018. Depressive mood and circadian rhythms disturbances as outcomes of seasonal affective disorder treatment: A systematic review. J Affect Disord. 241:608–626.

Mitra D, Steinmetz N, Chu Y, Cetin KS. 2020. Typical occupancy profiles and behaviors in residential buildings in the United States. Energy Build. 210. doi:10.1016/j.enbuild.2019.109713

Münch M, Wirz-Justice A, Brown SA, Kantermann T, Martiny K, Stefani O, Vetter C, Wright KPJ, Wulff K, Skene DJ. 2020. The role of daylight for humans: gaps in current knowledge. Clocks Sleep 2(1):61–85.

Olkin I, Finn JD. 1995. Correlations redux. Psychol Bull. 118(1):155–164.

PremiumLight Project Consortium. 2014. Top quality energy-efficient lighting for the domestic sector, Final report. Vienna (Austria): Austrian Energy Agency.

Rådberg J, Friberg A. 1996. Svenska stadstyper: historik, exempel, klassificering. 1st ed. [Swedish city types: history (examples, classification]. Stockholm (Sweden)): Kungliga Tekniska Högsklolan Stockholm.

Reinhart CF. 2005. A simulation-based review of the ubiquitous window-head-height to daylit zone depth rule-of-thumb. Paper presented at the 9th International IBPSA Conference; Montréal (Canada).

SCB. 2012. Swedish Time Use Survey 2010/11, Series title: LE - living conditions, in report 1654–1707 (Online); 0347–7193 (print). Örebro (Sweden): Statistics Sweden [accessed 2020 May 4] https://www.scb.se/publication/18561.

SCB. 2018. Dwelling stock 31/12/2018. Örebro (Sweden): Statistics Sweden [accessed 2020 May 4] https://www.scb.se/en/finding-statistics/statistics-by-subject-area/housing-construction-and-building/housing-construction-and-conversion/dwelling-stock/pong/statistical-news/dwelling-stock-2018-12-31/.

SCB. 2019. Completed dwellings and number of rooms including kitchen in newly constructed buildings by region and type of building, Year 1975–2018. Örebro (Sweden): Statistics Sweden [accessed 2020 May 2] http://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__BO__BO0101__BO0101A/LghReHustypAr/.

Schwarz N, Strack F, Mai H-P. 1991. Assimilation and contrast effects in part-whole question sequences: a conversational logic analysis. Public Opinion Q. 55(1):3–23.

Stevens RG, Rea MS. 2001. Light in the built environment: potential role of circadian disruption in endocrine disruption and breast cancer. Cancer Causes Controls. 12(3):279–287.

Stokes M, Crosbie T, Guy S. 2006. Shedding light on domestic energy use: a cross-discipline - study of lighting homes. Paper presented at the 2006 Annual Research Conference of the Royal Institution of Chartered Surveyors; London (UK).

Strack F, Martin LL. 1987. Thinking, judging, and communicating: a process account of context effects in attitude surveys. In: Hippler H-J, Schwarz N, Sudman S, editors. Social information processing and survey methodology. 1st ed. New York (USA): Springer New York; p. 123–148.

Tiller DK, Rea MS. 1992. Semantic differential scaling: prospects in lighting research. Light Res. Technol. 24(1):43–51.

Tourangeau R, Rasinski KA. 1988. Cognitive processes underlying context effects in attitude measurement. Psychol Bull. 103(3):299–314.

Ulrich RS. 1991. Effects of interior design on wellness: theory and recent scientific research. J Health Care Inter Des. 3:97–109.

Veitch JA, Hine DW, Gifford R. 1993. End-users' knowledge, beliefs and preferences for lighting. J Inter Des. 19(2):15–26.

Walch JM, Rabin BS, Day R, Williams JN, Choi K, Kang JD. 2005. The effect of sunlight on postoperative analgesic medication use: a prospective study of patients undergoing spinal surgery. Psychosom Med. 67(1):156–163.

Weiss B, Spies C, Piazena H, Penzel T, Fietze I, Luetz A. 2016. Exposure to light and darkness and its influence on physiological measures of intensive care unit patients-a systematic literature review. Physiol Meas. 37 (9):R73–R87.

Widén J, Lundh M, Vassileva I, Dahlquist E, Ellegård K, Wäckelgård E. 2009a. Constructing load profiles for household electricity and hot water from time-use data—modelling approach and validation. Energy Build. 41(7):753–768.

Widén J, Nilsson AM, Wäckelgård E. 2009b. A combined Markov-chain and bottom-up approach to modelling of domestic lighting demand. Energy Build. 41(10):1001–1012.

Wolf S. 2020. ProccS - an occupancy simulation tool for private households - Maintainer: sebastian Wolf [accessed 2020 May 14] https://www.proccs.org/index.

Wolf S, Calì D, Alonso MJ, Li R, Andersen RK, Krogstie J, Madsen H (2019). Room-level occupancy simulation model for private households. Paper presented at the CISBAT 2019 – International Scientific Conference; Lausanne (Switzerland).

Zimmermann ZP. 2009. End-use metering campaign in 400 households in Sweden - assessment of the potential electricity savings. Eskilstuna (Sweden): Swedish Energy Agency. Report No.: 17-05-2743. [accessed 2020 January 19]. https://www.enertech.fr/pdf/54/consommations%20usages%20electrodomestiques%20en%20Suede_2009.pdf

Zou GY. 2007. Toward using confidence intervals to compare correlations. Psychol Methods. 12(4):399–413.

LUND UNIVERSITY

ISSN 1671-8136
ISBN 978-91-85147-64-9