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Solar access in urban planning

Early-stage assessment of sunlighting and daylighting

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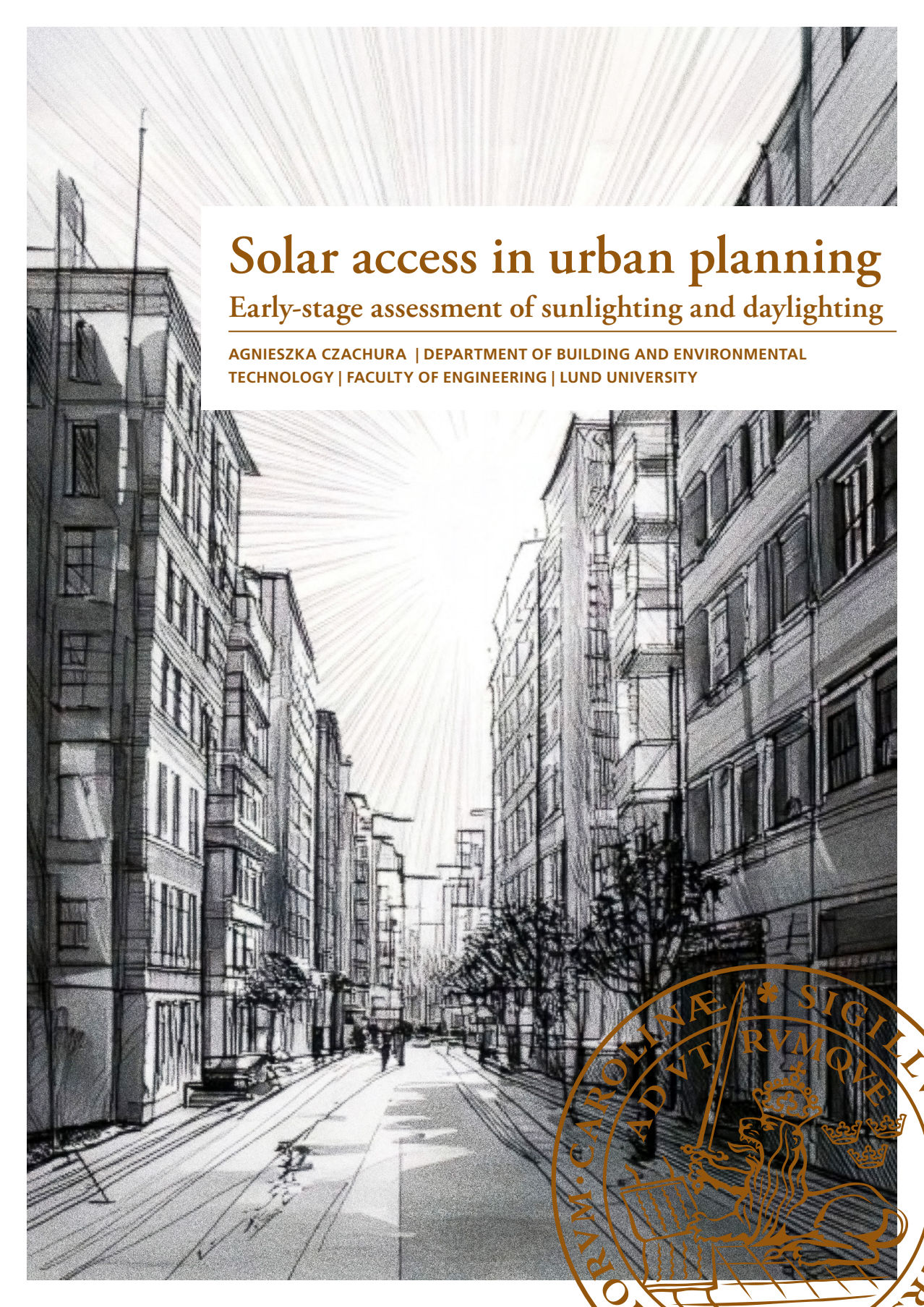
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An architectural sketch of a city street lined with multi-story buildings. Sun rays are drawn radiating from the horizon, illustrating the concept of solar access. The drawing is in a fine-line, sketchy style.

Solar access in urban planning

Early-stage assessment of sunlighting and daylighting

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Solar access in urban planning

Early-stage assessment of sunlighting and daylighting

Agnieszka Czachura



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DOCTORAL DISSERTATION

Doctoral dissertation for the degree of Doctor of Philosophy (PhD) at the Faculty of Engineering at Lund University to be publicly defended on 22 of May at 13.00 in V:A Hall, Department of Building and Environmental Technology, V-building:
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Abstract:

The densification of European cities presents a critical challenge for solar access, particularly in high-latitude Nordic climates. While urban planning in Sweden defines the geometric boundaries of future buildings, there is no statutory requirement to evaluate the resulting solar access at this stage. At later design stages, the Swedish Building Regulations (BBR) mandate daylighting provision, whereas sunlighting prescriptions have recently been removed. To safeguard solar access early on, urban planning requires assessment methods aligned with the low level of detail inherent to early design, as conventional climate-based metrics require indeterminate inputs.

Framed through the lens of habitability, this thesis investigated early-stage metrics capable of assessing the geometric capacity of neighbourhood designs to deliver daylighting and sunlighting into the urban fabric. Using a sequential mixed-methods approach, the research identified, calibrated, and evaluated early-stage solar access indicators. The indoor daylighting indicator—the Vertical Sky Component (VSC)—was calibrated against building standards to generate bespoke compliance targets. Simultaneously, the indoor sunlighting indicator was evaluated through simulations and in situ interviews to provide empirical evidence for sunlight provision in Sweden.

Regarding daylighting, the research demonstrated that compliance with modern standards (BBR and EN 17037) using the ubiquitous heuristic ($VSC \geq 27\%$) is conditional and often unattainable. Because compliance depends heavily on internal room geometry and Window-to-Floor Ratio (WFR), the study developed bespoke, design-based VSC thresholds for the Swedish context. These dynamic targets can be incorporated into digital urban planning tools to refine early assessments and support late-stage compliance.

Regarding sunlighting, empirical investigations confirmed that direct indoor sunlight is a highly valued amenity, though it carries inherent risks of visual and thermal discomfort. In high-latitude contexts with low solar angles, the findings indicate that adjustable shading devices should be considered a compulsory residential design element. To prevent sunlight scarcity and ensure baseline habitability, the research proposes a minimum regulatory prescription: disallowing apartments oriented exclusively toward the northern sector.

Ultimately, the indicators and methodologies proposed in this thesis provide an empirically derived framework for early-stage solar access assessment, ensuring that urban densification does not compromise the fundamental habitability of future residential environments.

Key words: habitability, urban densification, daylighting compliance, indoor sunlighting, building performance simulation (BPS), EN 17037, occupant satisfaction

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Solar access in urban planning

Early-stage assessment of sunlighting and daylighting

Agnieszka Czachura



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Abstract

The densification of European cities presents a critical challenge for solar access, particularly in high-latitude Nordic climates. While urban planning in Sweden defines the geometric boundaries of future buildings, there is no statutory requirement to evaluate the resulting solar access at this stage. At later design stages, the Swedish Building Regulations (BBR) mandate daylighting provision, whereas sunlighting prescriptions have recently been removed. To safeguard solar access early on, urban planning requires assessment methods aligned with the low level of detail inherent to early design, as conventional climate-based metrics require indeterminate inputs.

Framed through the lens of habitability, this thesis investigated early-stage metrics capable of assessing the geometric capacity of neighbourhood designs to deliver daylighting and sunlighting into the urban fabric. Using a sequential mixed-methods approach, the research identified, calibrated, and evaluated early-stage solar access indicators. The indoor daylighting indicator—the Vertical Sky Component (VSC)—was calibrated against building standards to generate bespoke compliance targets. Simultaneously, the indoor sunlighting indicator was evaluated through simulations and in situ interviews to provide empirical evidence for sunlight provision in Sweden.

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Ultimately, the indicators and methodologies proposed in this thesis provide an empirically derived framework for early-stage solar access assessment, ensuring that urban densification does not compromise the fundamental habitability of future residential environments.

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Popular science summary

Solar access in the densification era

To preserve natural land and resources, modern cities are growing inwards. However, placing buildings closer together inevitably reduces the amount of open sky visible from our windows, limiting the daylight and direct sunlight that reaches our homes. Currently, there is a critical disconnect in how cities are planned. While the Swedish building code dictates minimum light levels for final architectural designs, the urban planning stage—where building heights, shapes, and distances from one another are decided—lacks binding rules for good solar access.

Decisions made at this early "massing" stage determine the maximum available daylight and sunlight in the urban fabric and are irreversible without major interventions. Therefore, there is an urgent need to predict internal building compliance and future habitability during the planning phase, long before the architect draws the floor plans. This thesis addresses this gap by identifying suitable metrics to assess both indoor and outdoor daylighting and sunlighting provision at the city planning stage.

Measuring light before buildings exist

Historically, urban planners have relied on a "rule of thumb" stating that a specific amount of visible sky (a 27% Vertical Sky Component, or VSC) guarantees good indoor daylighting. This research demonstrates that this rule only works conditionally. In modern dense developments, relying on this old standard may force architects later in the process to use excessively large windows just to meet legal daylighting requirements.

To support more informed assessments, this research developed new, bespoke compliance-based targets. Rather than using one universal number, these targets link the amount of required open sky to the future room's shape and window size. By applying these new thresholds, urban planners can find out early on whether a proposed city block has a chance of compliance. They can also check whether it will require reasonably sized windows to meet daylighting regulations, preventing the negative consequences of over-dimensioned glazing, such as overheating and glare.

What do the residents want?

Beyond just meeting daylighting standards, the research explored how people actually experience direct sunlight access in their homes. Through a national survey and home-based interviews in Sweden, the results showed overwhelming support for sunlight: 90% of respondents want direct sunlight in their homes, where 67% welcome it year-round and 23% prefer to have sunshine at home only in wintertime.

However, this strong desire comes with practical challenges. While sunlight is vital for occupant satisfaction and psychological wellbeing, it also brings risks of summer overheating and screen glare. To make indoor spaces habitable and resilient, solar

control systems (such as awnings or blinds) are necessary to mitigate these risks. Preventing comfort inequalities, effective shadings should be integrated into the building design and not treated as an optional furnishing installed by the tenant.

Drawing on responses from the national survey, the study provides a practical guide for window orientation. This guide maps exactly when occupants prefer sunlight in specific rooms, highlighting the dominant preference for morning sun in kitchens and afternoon sun in living rooms.

Protecting natural light for everyone

Ultimately, this thesis advocates for socially sustainable cities designed for occupant wellbeing. It supports building laws that guarantee minimum daylight and sunlight, paired with effective solar control systems. This research is particularly timely given the recent deregulation in the Swedish building code, which removed explicit rules regarding indoor sunlight provision.

This deregulation introduces a risk: without explicit protections in the building code, sunlight may evolve from a guaranteed standard into a market commodity. By providing the tools and evidence needed to assess solar access early in the planning process, this research aims to ensure that natural light remains a fundamental standard of our living environments.

Populärvetenskaplig sammanfattning

Tillgång till solljus i förtätningens tid

För att bevara natur och jordbruksmark växer moderna städer inåt. Men när byggnader placeras tätare ihop minskar oundvikligen den synliga delen av himlen från våra fönster, vilket begränsar mängden dagsljus och direkt solljus som når in i våra hem. I dagsläget finns det en kritisk brist i hur städer planeras. Även om de svenska byggreglerna föreskriver miniminivåer av ljus i den färdiga arkitekturen, saknas det bindande regler för god tillgång till solljus i stadsplaneringsfasen – det skede där byggnadernas höjd, form och avstånd till varandra bestäms.

De beslut som fattas under detta tidiga skede när byggnadsvolymer bestäms, fastställer den faktiska gränsen för hur mycket dagsljus och solljus som överhuvudtaget kan nå in i stadsmiljön. Dessa beslut är i praktiken oåterkalleliga utan att enorma ingrepp görs. Därför finns det ett brådskande behov av att redan under planeringsfasen kunna förutsäga om byggnader kommer att uppfylla lagkrav och erbjuda en god boendemiljö, långt innan arkitekten ritar planlösningarna i ett senare skede. Avhandlingen adresserar denna brist genom att identifiera lämpliga måtvärden för att bedöma tillgången till både dagsljus och direkt solljus, såväl inomhus som utomhus, redan i stadsplaneringsskedet.

Att mäta ljus innan byggnader finns

Historiskt sett har stadsplanerare förlitat sig på en tumregel som säger att en viss andel synlig himmel (ett värde på 27 % för mätetalet Vertical Sky Component, eller VSC) garanterar bra dagsljus inomhus. Den här forskningen visar att den regeln bara fungerar under specifika förutsättningar. I moderna, täta stadsbyggnadsprojekt leder en övertro på denna gamla standard ofta till att arkitekter senare i processen tvingas rita in orimligt stora fönster bara för att uppfylla de lagstadgade dagsljuskraven.

För att möjliggöra mer välgrundade bedömningar har denna forskning tagit fram nya, skraddarsydda målvärden baserade på regelkraven. Istället för att använda en och samma siffra för alla projekt, kopplar dessa nya målvärden ihop hur mycket öppen himmel som krävs med det framtida rummets form och fönsterstorlek. Genom att tillämpa dessa förfinade gränsvärden kan stadsplanerare tidigt se om ett förslaget stadskvarter kommer att tvinga fram grunda rum eller överdimensionerade fönster för att uppfylla ljuskraven, och därmed förhindra negativa konsekvenser av för mycket glas i fasaden.

Vad vill de boende ha?

Utöver att bara uppfylla myndigheternas krav på ljus, undersöktes hur människor faktiskt upplever direkt solljus i sina hem. Genom en nationell enkätundersökning och hemintervjuer i Sverige visade resultaten på ett överväldigande stöd för solljus: 90 % av de tillfrågade vill ha direkt solljus i sina hem, varav 67 % vill ha det året runt och 23 % föredrar det enbart på vintern.

Denna starka önskan för dock med sig praktiska utmaningar. Samtidigt som solljus är avgörande för de boendes trivsel och psykologiska välbefinnande medför det också risker för övertemperaturer på sommaren och bländande ljus på skärmar. För att göra inomhusmiljöer drägliga under hela året krävs solskyddssystem (som till exempel persienner eller markiser) för att hantera dessa risker. För att förhindra ojämlikheter i komfort bör effektiva solskydd integreras i byggnadens utformning och inte behandlas som en valfri inredningsdetalj som installeras av hyresgästen.

Baserat på den nationella enkäten ger studien praktiska råd för hur fönster bör orienteras. Den visar exakt när på dagen de boende helst vill ha in solljuset i olika rum – till exempel den tydliga önskan om morgonsol i köket och eftermiddagssol i vardagsrummet.

Att skydda rätten till dagsljus för alla

Sammanfattningsvis förespråkar denna avhandling socialt hållbara städer som utformas med människors välbefinnande i fokus. Den stödjer byggregler som kräver miniminivåer för både dagsljus och direkt solljus inomhus, kombinerat med fungerande solskyddssystem. Denna forskning är särskilt aktuellt med tanke på de senaste ändringarna i de svenska byggreglerna, där det uttryckliga kravet på direkt solljus har tagits bort.

Denna avreglering medför en risk: utan tydliga regler i bygglagstiftningen kan rätten till solljus komma att ändras från att vara en garanterad standard till att bli en ren handelsvara. Genom att tillhandahålla de bevis och mätmetoder som krävs för att korrekt kunna bedöma tillgången till solljus tidigt i planeringsprocessen, syftar denna forskning till att säkerställa att naturligt ljus förblir en tillgänglig och självklar standard i våra livsmiljöer.

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Finally, to everyone else who played a part in this journey, no matter how big or small: whether you offered a passing word of encouragement, helped me solve a problem, or simply shared a smile—your kindness mattered.

Thank you. Tack. Dziękuję.

Terminology

This chapter defines the key concepts and metrics used throughout this thesis.

Annual Sunlight Hours (ASH)

A latitudinal metric measuring the cumulative duration of direct sunlight received at a specific point (e.g., on a façade or window) over a whole year. In this research, it serves as the primary early-stage indicator for predicting indoor sunlighting.

Daylight

The visible portion of the solar electromagnetic spectrum (approximately 380–740 nm). It encompasses both direct sunlight and diffuse skylight.

Daylighting

The architectural practice and regulatory requirement of providing adequate natural illumination, typically for indoor spaces.

Detailed Development Plan (DDP)

Swedish: *Detaljplan*. A legally binding municipal planning instrument in Sweden that regulates land use, building volumes (massing), placement, and maximum heights. It establishes the geometric boundary conditions prior to the detailed architectural design phase. It is governed by the Planning and Building Act (*Plan- och bygglag*, PBL).

Floor Area Ratio (FAR)

A geometrical metric expressing urban density or compactness, calculated as the ratio of the gross floor area of buildings to their site area. It does not account for variations in floor height.

Indicator

A specific metric selected and utilised as a reliable proxy to quantify performance and achieve design objectives.

Metric

A quantifiable measure used to evaluate a specific physical, temporal, and/or geometric parameter of a design. In this research, solar access metrics are systematically categorised based on their input complexity and computational demand.

Reference Day (RD) Sunlight Hours

See: Sunlight Hours on 21st March (SH 21/3)

Sky View Factor (SVF)

The geometric ratio between the visible area of the sky and the total theoretical sky dome, evaluated at a discrete point on a horizontal surface.

Solar Access

An overarching concept describing the availability of both direct sunlight and diffuse daylight within the urban fabric and indoor spaces. It represents the geometric and environmental potential of a specific location to receive solar radiation.

Solar Control

An umbrella term including physical design interventions—most notably shading devices and glazing parameters—intended to modulate solar access.

Solar Provision

The deliberate act of designing urban forms and architectural layouts to secure solar access for a given space. While solar access describes the resulting passive state or physical availability of light, solar provision refers to the conscious planning decisions—such as massing, orientation, and spatial configuration—employed by designers and planners to achieve that state.

Solar Radiation

The total electromagnetic energy emitted by the sun, quantified as radiant flux. It is typically divided into direct (sunlight) and diffuse (skylight) components.

Sunlight Hours on 21st March (SH 21/3)

A latitudinal metric quantifying the connectedness of a surface (façade or ground) to the sunpath on the spring equinox. It measures the duration of cloudless direct sunlight received at a specific point, typically simulated hourly. This metric forms the basis of the sunlighting recommendations in the European standard EN 17037, which stipulates a minimum sunlight exposure (1.5 hours) at a reference point in an aperture. Note: In appended publication (Paper II), this metric is referred to as Reference Day (RD) Sunlight Hours.

Sunlighting

The architectural practice and regulatory requirement of providing adequate direct sunlight exposure to indoor spaces. It refers to the capacity of a space or surface to receive direct solar rays. Unlike daylighting, which is fundamentally concerned with illumination levels for visual tasks, sunlighting is typically quantified by the temporal duration of exposure (e.g., hours) rather than radiant intensity.

Vertical Sky Component (VSC)

A geometrical metric calculated at a single point on a vertical façade, representing the ratio of illuminance received at that point to the total potential illuminance on an unobstructed horizontal plane. It assumes a CIE overcast sky model and accounts for no reflections. In this research, it serves as the primary early-stage indicator for predicting indoor daylighting.

Volume Area Ratio (VAR)

A morphological geometrical metric representing built urban density, calculated as the ratio of the total volume of buildings to the site area. Unlike FAR, VAR accounts for the vertical dimension of the massing, making it a stronger control variable and early-stage indicator for assessing the relationship between urban form and solar access.

Window-to-Floor Ratio (WFR)

A geometric metric expressing the proportion of window area relative to the total floor area of the space it illuminates. It is calculated per room or per dwelling. While building physics often distinguishes between a window ratio (which includes the opaque frame) and a glazing ratio (which strictly considers the transparent glass), in the context of this thesis, WFR is calculated using only the glazed area. WFR directly links the aperture size to the internal floor area requiring illumination, providing a stronger correlation to daylighting analysis than the commonly used Window-to-Wall Ratio (WWR).

Window-to-Wall Ratio (WWR)

A geometric metric expressing the proportion of window area relative to the area of the external wall on which it is located, calculated either for a whole building or a part of the external wall. As with WFR, this thesis calculates WWR based exclusively on the active glazed area, excluding the frame. While WWR is traditionally used in architectural design and energy performance assessments (such as for calculating thermal transmittance), it is less effective than WFR as a standalone predictor of indoor daylight distribution.

List of publications

Appended publications

- Paper I:* Czachura, A., Kanters, J., Gentile, N., & Wall, M. (2022). Solar performance metrics in urban planning: A review and taxonomy. *Buildings*, 12(4), 393. <https://doi.org/10.3390/buildings12040393>
- Paper II:* Czachura, A., Gentile, N., Kanters, J., & Wall, M. (2022). Identifying potential indicators of neighbourhood solar access in urban planning. *Buildings*, 12(10), 1575. <https://doi.org/10.3390/buildings12101575>
- Paper III:* Czachura, A., Kanters, J., Wall, M., & Gentile, N. (2024). Enhancing daylighting predictions in urban planning: A workflow for setting bespoke Vertical Sky Component (VSC) targets. *Building and Environment*, 266, 112066. <https://doi.org/10.1016/j.buildenv.2024.112066>
- Paper IV:* Czachura, A., Kanters, J., & Gentile, N. (2025). *Sunlight in Swedish homes: A mixed-methods study on perceptions, preferences, and building standards*. Manuscript submitted for publication to LEUKOS - The Journal of the Illuminating Engineering Society. Under review.
- Paper V:* Czachura, A., Gentile, N., Kanters, J., & Wall, M. (2025). *Sunlight at home: Exploring preferences and their impact on building design*. Manuscript accepted for publication in the proceedings of the 2025 Solar World Congress.

Contribution statement

The specific contributions of the author and co-authors to each publication are defined below according to the CRediT (Contributor Roles Taxonomy) standard. The authors are referred to by their initials: AC (Agnieszka Czachura), JK (Jouri Kanters), MW (Maria Wall), and NG (Niko Gentile).

- Paper I:* Conceptualisation: AC, JK, MW, NG; Methodology: AC, JK, MW, NG; Formal Analysis: AC; Investigation: AC; Writing – Original Draft: AC; Writing – Review & Editing: AC, JK, MW, NG; Visualisation: AC; Supervision: JK, MW, NG; Project Administration: JK, MW; Funding Acquisition: JK, MW.
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Declaration of AI use

The author declares the use of artificial intelligence (AI) language models in the drafting of this thesis (*kappa*). AI-powered research assistants were used for literature scoping and initial information retrieval; all sourced data and citations were subsequently manually reviewed and verified by the author. Additionally, Large Language Models were employed as editorial assistants to conceptualise the structure, refine syntax, improve readability, and ensure academic tone of the text. The author takes full responsibility for the factual accuracy, original intellectual content, and the final text of this document.

Other publications

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1. Introduction

1.1. Urban densification and solar access

Rapid urbanisation has introduced densification as the predominant paradigm in contemporary city planning, driven by the imperative to preserve agricultural land and curb urban sprawl (European Commission, 2019; Lisberg Jensen et al., 2023; Seto et al., 2011; United Nations, 2017). Within this context, scientific consensus establishes solar radiation as a key driver of both building performance and human health (Aries et al., 2015; IEA SHC, 2022). The European nZEB framework combines low energy demand with a high share of on-site or nearby renewables, with EU guidance now requiring new buildings to be designed to optimise solar energy generation, making solar access a key design parameter (European Parliament & Council of the European Union, 2024).

The concept of urban solar access comprises two functional components: daylighting and sunlighting. While often used interchangeably, these terms represent distinct design objectives. The primary role of daylighting is to fulfil a visual requirement, whereas sunlighting drives thermal performance and psychological satisfaction. Beyond natural illumination, daylight exposure is also a key determinant of wellbeing in the built environment (Altomonte et al., 2020; Aries et al., 2015). Yet the literature highlights the double-edged nature of solar exposure. While daylight and sunlight are critical for vitamin D synthesis (Holick, 2004), circadian regulation (Wirz-Justice et al., 2021) and mental health (Rosenthal et al., 1984; Wang et al., 2023), studies consistently show that uncontrolled solar exposure poses significant risks of glare and overheating (Aries et al., 2015; Farahani et al., 2024; Moretti & Belloni, 2015; Schade et al., 2025).

Achieving optimisation in densifying cities requires a nuanced understanding of urban form. The inverse relationship between urban density and solar access has been demonstrated in studies of existing multi-family stocks and simulated densification scenarios (Bournas & Dubois, 2019; Lee et al., 2016). Research emphasises that density alone—commonly expressed as Floor Area Ratio (FAR)—is a poor proxy for solar performance (Zhang et al., 2012). For example, Zhang et al. (2019) and Martinelli and Matzarakis (2017) have demonstrated that distinct typologies offer significantly different solar performance profiles even at equivalent densities. This distinction suggests that the overshadowing effect is not solely a

consequence of density but emerges from the interaction between urban density and urban morphology.

1.2. The European regulatory framework

Regulations for indoor solar access in Europe consist of unified continental standards, individual national building codes, and historical legal frameworks as the UK's "Rights to Light". Despite a general consensus on the need for natural light (Aries et al., 2015; SIS & CEN, 2021), the specific mandates regarding quantitative daylight thresholds and direct sunlight provision targets significantly across jurisdictions.

At the European level, solar access is guided by the EN 17037 standard ("Daylight in buildings"), which provides a multi-tiered framework for evaluating both daylight and sunlight (SIS & CEN, 2021). Rather than a singular mandate, EN 17037 defines three distinct performance levels. For direct sunlight exposure, the standard recommends a minimum of 1.5 hours, scaling up to 3 hours (medium) and 4 hours (high), measured at the aperture's reference point on a cloudless reference day. For daylight provision, EN 17037 establishes geographically dependent targets and offers two compliance pathways: 1) annual spatial illuminance thresholds based on Climate-Based Daylight Modelling (CBDM), and 2) a static Daylight Factor (DF) method using location-adjusted thresholds. Previous studies indicate that the illuminance-based CBDM pathway yields higher compliance rates compared to the DF method (Bournas, 2020; Dervishaj et al., 2022; Jin et al., 2025). In countries such as Germany and the UK, this voluntary European standard has been adopted and functions as the expected benchmark for good practice (Jakobiak, 2021; Littlefair et al., 2022).

Despite the existence of the EN 17037 standard in Europe, national building codes remain the legal baseline, resulting in diverse national approaches to solar access (Table 1).

The Scandinavian approach prioritises daylighting over sunlighting. For instance, Sweden, Denmark, and Norway mandate minimum daylighting targets but no specific sunlighting minima exist in their respective building codes (Table 1). The Swedish daylighting metric allows for spatial compensation, meaning a highly illuminated bedroom can offset a gloomy living room to comply with the aggregate 1% DF target—a baseline that is demonstrably less stringent than the minimum daylight provisions of EN 17037 (Jin et al., 2025). Notably, the 2024 revisions to the Swedish building regulations (*Boverkets byggregler*, BBR) deregulated indoor sunlight provision, removing the previous mandate that required at least one room to receive direct sunlight despite lacking a quantified minimum duration or time frame (Boverket, 2011, 2024).

Table 1

Comparison of national daylighting and sunlighting mandates across selected European countries.

Country	Daylighting Mandate	Sunlighting Mandate	Source
Sweden	≥ 1% Daylight Factor (DF) in half of the combined floor area of occupied rooms <i>(before 2025: ≥ 1% DF at a point halfway into the room, 1 m away from the darkest wall)</i>	None <i>(before 2025: at least one frequently occupied room should have direct sunlight access)</i>	(Boverket, 2024)
Norway	≥ 2% average Daylight Factor (DF)	None	(Direktoratet for byggkvalitet, 2017)
Denmark	Glazing-to-floor ratio ≥ 10% for living rooms and kitchens, or illum. ≥ 300 lux for 50% space and 50% daylight hours	None	(Social- og Boligministeriet, 2018)
Poland	Window-to-Floor Ratio (WFR) ≥ 12.5% in occupied rooms	≥ 3 h on equinoxes (7:00–17:00) for at least one room, reduced to 1.5 h in urban centres	(Ministerstwo Infrastruktury, 2002)
UK <i>(not legally binding)</i>	EN 17037 for interiors, BRE for site planning: ≥ 27% Vertical Sky Component (VSC)	EN 17037 & BRE: ≥ 1.5 h on a ref. day (1/2-21/3), BRE: at least one main window within 90° of south orientation	(British Standards Institution, 2021; Littlefair et al., 2022)

These specific technical codes derive their legal authority from a broader statutory framework. Swedish urban development is governed by the Planning and Building Act (*Plan- och bygglag*, PBL), which legally mandates the promotion of socially sustainable and long-term habitable living environments (Sveriges Riksdag, 2010). While the PBL does not specify quantitative daylight or sunlight thresholds, it states that buildings and urban massing must be designed to ensure good climatic and hygienic conditions, alongside the provision of suitable outdoor spaces for recreation. This overarching legislation establishes human-centric environmental standards as a qualitative legal prerequisite, relying on subordinate regulations like the BBR to translate those goals into enforceable targets.

In contrast to the Scandinavian deregulation, Poland enforces one of the most stringent national mandates for sunlight access in Europe (Table 1). The country maintains a legally binding prescriptive regulation for sunlight duration that exceeds the EN 17037 minimum. To structurally guarantee this provision, the regulations essentially prohibit apartments consisting of two or more rooms from being oriented exclusively towards the north. However, the Polish framework explicitly acknowledges the geometric conflict between solar access and urban densification by incorporating a specific relaxation clause: buildings located within downtown city-centre developments are permitted to halve the required sunlight duration from 3 hours to 1.5 hours, while single-room apartments are exempt from the rule. Conversely, while these sunlighting mandates are highly prescriptive, Poland adopts a simplified approach to daylight provision. Instead of requiring advanced climate-

based daylight modelling or dynamic simulations, the Polish daylight standard relies exclusively on a minimum Window-to-Floor Ratio (WFR) without necessitating any location-specific climatic evaluation.

The UK approaches solar access through a hybrid system integrating EN 17037, specific national guidelines, and historical property law. The primary standard (BS EN 17037:2018+A1:2021) operates in conjunction with the Building Research Establishment (BRE) Report 209 (Littlefair et al., 2022). In practice, both documents serve complementary roles during planning assessments: BRE 209 guides site layout and external massing through metrics such as the Vertical Sky Component (VSC), whereas BS EN 17037 evaluates the resulting internal daylight provision. Although these documents lack strict legal enforceability, they function as the *de facto* industry benchmarks.

For new developments, the BRE guidelines stipulate that at least one main window wall faces within 90° of due south, and that a primary habitable room receives a minimum of 1.5 hours of sunlight on the spring equinox (Table 1). To ensure adequate "light from the sky" at the façade level, the BRE recommends a VSC of 27%. Outdoor amenity spaces are also recommended to have at least 50% of the area receiving two hours of direct sunlight on 21st March.

Furthermore, the BRE report contains explicit guidelines for protecting the daylight and sunlight access of existing buildings. It provides methodologies for measuring the potential loss of light caused by new developments, effectively preventing construction from encroaching too closely upon adjoining land. For instance, to assess and protect existing buildings from excessive overshadowing, the guidelines propose evaluating the reduction of Annual Probable Sunlight Hours (APSH).

Development in the UK is also constrained by the "Rights to Light," a unique private legal easement established under the Prescription Act 1832 (UK Parliament, 1832). It states that if a window has enjoyed uninterrupted natural light for 20 years, the property owner acquires a legally protected right to that light. This right is entirely independent of modern planning permissions or EN 17037 compliance. It serves as a powerful legal instrument, allowing existing property owners to seek injunctions or compensation against new developments that cause substantial obstruction of their established natural light access.

1.3. The solar access research landscape

Urban density and morphology are universally identified across the literature as the primary determinants of solar access. Systematic reviews and global meta-analyses demonstrate that parameters such as density ratio, street canyon aspect ratio, verticality, site coverage, and Sky View Factor (SVF) steer urban potential for both

solar energy generation and passive indoor solar availability (Köker et al., 2025; Li et al., 2025; Rostami & Nasrollahi, 2025). The spatial distribution of massing determines active solar potential, with data-driven studies identifying building density and height variation as critical predictive variables for neighbourhood-scale energy output (Lan et al., 2022).

The impact of morphology is amplified in high-latitude climates. In these contexts, the interplay between compact urban forms and characteristically low solar altitudes makes building façades—rather than solely rooftops—critical solar receivers. Consequently, specific morphological considerations and spacing are required to optimise solar exposure in Nordic environments (Formolli et al., 2023, 2024; Giorio et al., 2024, Kanters & Wall, 2014).

Parallel to morphological research, the quantification of daylight and sunlight has evolved from rudimentary, static thresholds to dynamic, climate-responsive evaluations. Conventionally, sunlight access has been quantified through simplified geometric methods, but researchers note these methods struggle to capture the complex temporal and climatic variability of the sky (Mardaljevic, 2006).

Recent research emphasises the need for multidimensional assessments that account for diurnal and seasonal nuances (Dogan & Park, 2019). Contemporary work critiques existing standards such as EN 17037, noting that their reliance on fixed days and rigid solar exposure thresholds introduces substantial inaccuracies, particularly in high-latitude Nordic regions (Dervishaj & Gudmundsson, 2025). To address these limitations, they demonstrate how new annualised metrics—such as Sunlight Autonomy—offer more temporally representative evaluations, revealing significant regional discrepancies when compared to static compliance criteria. Alongside these temporal metrics, integrated frameworks like the Sunlight-Daylight Signature combine obstruction geometry with sky visibility, allowing for a more comprehensive, perception-oriented classification of urban solar environments (Lo Verso et al., 2023).

The advancement of daylighting science has heavily influenced modern building regulations, notably the European standard EN 17037. However, the academic literature documents substantial friction between these compliance thresholds and practical urban planning (Bournas, 2020; Šprah & Košir, 2020). Analytical evaluations conducted in cold and high-latitude climates indicate that the daylighting targets stipulated by EN 17037 can be impractically stringent, often failing to account for regional atmospheric turbidity and low sun angles (Sepúlveda et al., 2022).

Furthermore, there is an inherent conflict between solar access regulations and the imperative for urban densification. Because compact block layouts inherently limit sky visibility, pursuing high urban density without adequate early-stage evaluation often locks in massing configurations that render subsequent architectural daylight compliance physically unattainable (Bournas, 2020; Šprah & Košir, 2020). While

researchers have successfully modernised early-stage Solar Envelope methods to computationally optimise building massing against complex sunlight ordinances (De Luca & Dogan, 2019), predicting indoor daylight performance from exterior massing remains methodologically complex. Consequently, there remains a distinct lack of established, validated early-design workflows capable of ensuring late-stage daylight compliance.

To navigate the friction between early-stage urban densification and late-stage architectural compliance, a substantial body of research focuses on simplifying assessments. Because detailed climate-based simulations are computationally demanding and highly sensitive to undefined architectural variables, researchers stress the need for computationally light proxy metrics during conceptual massing phases (Chatzipoulka et al., 2018; Kanters et al., 2021; Nault et al., 2015).

Beyond indoor habitability, solar access profoundly influences outdoor microclimates and the urban heat island effect, as the interaction between solar radiation and urban geometry impacts both heat storage and cooling loads (Phelan et al., 2015). In this context, studies emphasise that urban canyon morphology governs the critical trade-off between securing necessary daylight availability and mitigating the risks of excessive insolation during hot summer periods (Nasrollahi & Rostami, 2023). Consequently, research strongly supports integrated design strategies where geometric solar optimisation is paired with mitigation measures—such as strategic shading and green infrastructure—to balance solar access with urban temperature regulation (Hwang et al., 2018).

1.4. Problem statement

While high-density compact cities are widely promoted for their environmental and economic efficiency (United Nations, 2018, 2019)—preserving land and consolidating infrastructure—this morphological transformation creates a fundamental paradox regarding social sustainability (Mattson, 2015). Although human health and psychological wellbeing are inextricably linked to natural light exposure, densification inherently restricts sky visibility (Bournas & Dubois, 2019), thereby compromising the very sustainability goals it seeks to achieve.

Despite the critical importance of solar access, a significant legislative void exists at the intersection of urban planning and building design, particularly in the Swedish context. While the final building object must comply with strict, performance-based rules—namely, the daylighting mandates of the Swedish BBR—no equivalent regulatory framework exists for the Detailed Development Plan (DDP) stage, where the primary massing, orientation, and urban density are legally restricted (Sveriges Riksdag, 2010). At this early phase, municipal urban planners operate exclusively under the Planning and Building Act (PBL), which contains no quantitative

requirements for natural light. Because the BBR requirements are only imposed on property developers during the later building permit phase, this regulatory misalignment means planners may inadvertently approve massing geometries that make it physically impossible for developers to subsequently comply with the daylighting prescriptions (Kanters et al., 2021).

This disconnect stems from a misalignment between the static, geometrical nature of urban planning and the dynamic, data-intensive nature of building compliance. Lacking validated translation mechanisms, planners face a critical deficiency in assessment capabilities. For instance, Climate-Based Daylight Modelling (CBDM)—increasingly demanded by green building certifications and advanced compliance frameworks—relies on unavailable architectural detail, making it effectively inapplicable at the planning stage (Mardaljevic, 2021). As Nault et al. (2015) argue, early-stage massing requires computationally efficient metrics that can function with limited data.

Consequently, practice remains reliant on simplified heuristics, most notably the VSC and static rules of thumb (Chatzipoulka et al., 2018; Littlefair, 2001; Littlefair et al., 2022). However, these heuristics lack empirical calibration against modern daylighting standards and different locations (Bournas, 2020; Olina & Zaimi, 2018; Šprah & Košir, 2020), creating a significant risk of performance gaps.

Furthermore, a regulatory asymmetry exists: while planning routines often prioritise daylight compliance – driven by mandatory national targets (Kanters et al., 2021) – sunlight access is frequently treated as a secondary objective. This divide is now being exacerbated by recent revisions to the Swedish BBR, which deregulated direct sunlight provision while retaining daylighting mandates (Boverket, 2024). This imbalance creates a risk that urban form is optimised solely for visual criteria, neglecting the critical psychophysiological benefits of direct solar exposure.

The consequences of poor solar access planning are often irreversible. When a DDP permits excessive obstruction, the subsequent architectural design phase is forced to adopt compensatory measures to meet legal daylight requirements. This typically results in the adoption of high glazing ratios (Chokhachian et al., 2020). While large windows may satisfy daylight mandates, they introduce a secondary liability: an increased risk of summer overheating and glare combined with increased energy demands (Czachura & Davidsson, 2021).

There remains also a significant qualitative gap regarding human satisfaction. Compliance with a minimum standard does not necessarily equate to occupants' wellbeing. In high-latitude contexts such as Sweden, ensuring sufficient solar access for improved wellbeing during the cold light-deprived winter months simultaneously creates indoor comfort risks related to low-angle glare and summer overheating (Grynning et al., 2014; Kownacki et al., 2019). Existing empirical evidence regarding residential preferences in temperate climates is largely outdated (Bitter & Van Ierland, 1965; Gilgen & Barrier, 1976; Ne'eman et al., 1976). There

is a need to re-evaluate how modern occupants perceive and value sunlight to ensure that quantitative targets align with qualitative human needs.

1.5. Aim and research questions

The primary aim of this thesis is to bridge the gap between early-stage urban planning for solar access and the late-stage objectives of building performance and occupant satisfaction. To this end, the research identifies, calibrates, and evaluates metrics that may serve as reliable proxies for regulatory compliance and user preference. By identifying which metrics effectively link urban form to solar access potential, and demonstrating how they can be operationalised, the work aims to enable more informed assessments and support decision-making at the urban planning stage.

The scope of this research is delimited to the geo-climatic and legislative context of high-latitude regions, specifically Sweden. This geographic focus is necessary because the regulatory mechanisms governing urban planning may differ in other countries, even within Scandinavia. The investigation focuses exclusively on residential neighbourhoods. Furthermore, the work concentrates on the passive provision of daylight and sunlight; the potential for active solar energy systems is explicitly excluded from this analysis to maintain focus on the indoor environmental quality and habitability aspects of the urban fabric.

To achieve the stated aim, the research is led by three main research questions (RQs), which correspond to the sequential phases of the methods:

- *RQ1 (Definition & identification):*
Which simple metrics can be used as indicators of solar access (sunlighting and daylighting) in the assessment of early-stage urban plans and building designs? (Addressed in Paper I & Paper II)
- *RQ2 (Operational calibration):*
How can the identified early indicator of indoor daylighting be calibrated to ensure compliance with regulatory standards? (Addressed in Paper III)
- *RQ3 (Qualitative evaluation):*
How do quantitative indoor sunlighting metrics align with human perception and satisfaction in high-latitude residential contexts? (Addressed in Paper IV & Paper V)

1.6. Methodological overview

The research presented in this thesis employs a sequential mixed-methods design. The investigation is organised into three distinct methodological phases (Figure 1), corresponding directly to the research questions (Table 2). Moving from the definition and identification of metrics (Phase 1) to operational calibration (Phase 2) and finally to qualitative evaluation of their application (Phase 3), the research provides solar access assessment workflows which address both the regulatory requirements and the needs of residents.

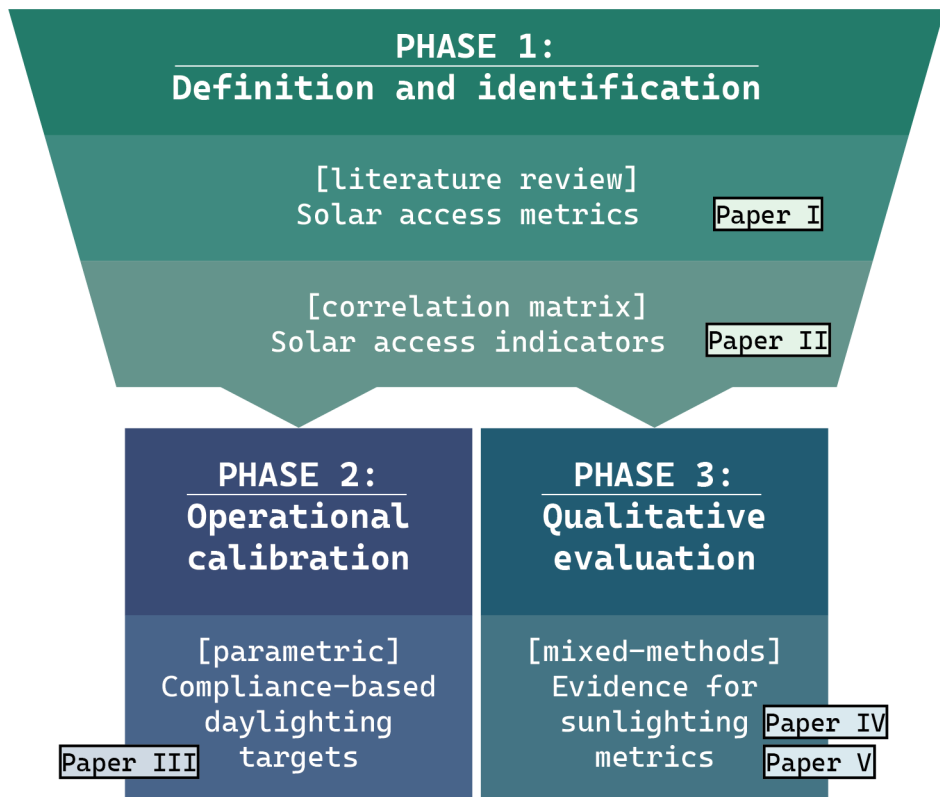


Figure 1
Methodological overview of the thesis.

Table 2

Methods used in the thesis.

Appended paper	Paper I	Paper II	Paper III	Papers IV & V
Phase	1	1	2	3
Research strategy	Literature review	Simulations	Simulations	Field study + simulations
Methods	Integrative review via Scopus database Taxonomic classification	Parametric design iterations and case studies Simulations in Rhino 3D Correlation analysis (Kendall, Pearson) Statistical methods	Parametric design iterations Simulations in Rhino 3D ROC analysis Bespoke method for setting compliance-based targets	Semi-structured interviews and in situ survey Measurements Public survey Simulations in Rhino 3D Thematic analyses Statistical methods
Research question	RQ1	RQ1	RQ2	RQ3

1.6.1. Phase 1: Definition and identification (Papers I & II)

The initial phase—previously published as a licentiate thesis (Czachura, 2023) and detailed in Chapter 2 of this thesis—focused on defining the appropriate metrics for early-stage solar assessment to address RQ1. This was achieved through a combination of theoretical and computational methods.

First, an integrative literature review (Paper I) mapped the existing landscape of solar access metrics, creating a taxonomy of existing metrics based on input complexity. This step defined and assessed metric categories to determine their suitability for urban planning and early-stage design applications.

To select the most suitable metrics from the taxonomy, the next step (Paper II) employed parametric simulations using iterations of three common neighbourhood typologies (courtyard, slab, and tower) and existing case-study neighbourhoods in Malmö. Selected metrics were calculated for the external façade and ground surfaces to quantify interior and exterior solar access of the neighbourhood designs. A Kendall rank correlation analysis evaluated the relationships between urban morphology, density, and the selected solar access metrics, identifying specific indicators suitable for early-stage performance assessment. The parametric design iterations were created and simulated in the Grasshopper environment within Rhino using Ladybug Tools (Ladybug Tools, 2021; Robert McNeel & Associates, 2020b, 2020a). Statistical analyses were performed using R in RStudio (RStudio Team, 2021).

1.6.2. Phase 2: Operational calibration (Paper III)

The second phase (presented in Chapter 3.1) focused on the operational calibration of the identified indoor daylighting indicator to answer RQ2. This step employed a parametric simulation of a single-aspect room, iterating through geometric permutations of the room ratio, window size, and window orientation. Simulations calculated internal daylighting performance according to BBR and EN 17037 standards across varying degrees of external obstruction, correlating compliance outcomes with the corresponding metric values. This process generated calibrated compliance targets for the daylighting indicator, enabling preliminary assessment of regulatory compliance during early design stages. The parametric design iterations were modelled in Grasshopper through Rhino (Robert McNeel & Associates, 2020b, 2020a), while the simulations were performed using Ladybug Tools (Ladybug Tools, 2021).

1.6.3. Phase 3: Qualitative evaluation (Papers IV & V)

The final phase (presented in Chapter 3.2) introduced a qualitative investigation to explore the human relevance of the selected indoor sunlighting metrics and address RQ3. Recognising that sunlighting involves physical and psychological impacts, this phase employed a mixed-methods approach. Seven apartments located in Lund and Malmö were investigated. Data collection involved in situ semi-structured interviews, physical measurements of the visited apartments, and a large-scale online survey. The neighbourhoods of the visited apartments were modelled based on available geodata (Lantmäteriet, 2025). The models were created using an FME script (Safe Software, 2021) and imported into Rhino (Robert McNeel & Associates, 2020b). The sunlight exposure was simulated in Grasshopper (Robert McNeel & Associates, 2020a) using Ladybug Tools (Ladybug Tools, 2021). The interview transcripts and survey comments were analysed and coded in NVivo 14 (Lumivero, 2023). The study explored the relationship between the simulated quantitative sunlighting metrics and the perceived satisfaction, offering insights into occupant preferences and the relevance of existing sunlighting thresholds.

1.7. Scope and delimitations

The quantitative thresholds, metric evaluations, and simulated environments are specifically calibrated to high-latitude contexts. The findings are primarily applicable to Nordic climates, where low sun angles and specific overcast sky conditions dominate, and may not directly translate to other latitude regions with different sun paths and climatic realities.

The research is strictly anchored in the regulatory frameworks governing Swedish and European built environments. Methodologically, it targets the early-stage municipal planning phase—specifically the Swedish DDP. The performance evaluations are delimited to the benchmarks set by the Swedish BBR and the EN 17037. The spatial scale of the investigation is confined to residential urban blocks and neighbourhoods.

This thesis frames solar access exclusively through the lens of habitability, focusing on the provision of daylight and direct sunlight to support occupant health and wellbeing. Consequently, the assessment of active solar energy generation systems and building energy performance is explicitly excluded from the research scope.

2. The solar access framework

This chapter presents Phase 1 of the methodology to answer RQ1: *Which simple solar metrics can be used as indicators of solar access in the assessment of early-stage urban plans and building designs?* First, this chapter defines the rationale for solar access in the urban environment. The chapter then outlines the European regulatory framework governing these objectives and maps the current scientific discourse within the solar access research landscape. Anchored in this context, the chapter transitions to the findings of Paper I and Paper II, constructing a taxonomy of performance metrics and identifying the specific indicators required to overcome the regulatory disconnect in early-stage planning.

2.1. Solar access in the urban environment

Solar access is broadly defined as the capability of a specific point or space to receive direct radiation from the sun and diffuse light from the sky vault. In the built environment, this availability underpins two intersecting, yet often competing, performance objectives: occupant wellbeing and energy efficiency. As a foundational principle, the provision of daylight and sunlight is a requirement grounded in social sustainability and human health. While strategically oriented glazing can actively improve a building's energy balance through passive solar gain, treating energy efficiency as the sole optimisation parameter would result in largely opaque envelopes punctuated only by mathematically optimised, sun-facing apertures. Therefore, the ubiquitous integration of windows across diverse façades and orientations serves primarily to satisfy psychophysiological human needs, ensuring spaces are habitable for people even when it requires a compromise in thermal optimisation.

As illustrated in Figure 2, solar access indoors—comprising both daylighting and sunlighting—exerts direct and indirect impacts on human comfort and building energy loads. The figure maps how these solar components directly influence thermal and visual comfort (the wellbeing domain), which in turn affect heating, cooling, and lighting needs (the energy efficiency domain). While energy loads typically demand minimisation, human comfort relies on a carefully calibrated equilibrium rather than simple maximisation. Consequently, the underlying provision of daylighting and sunlighting requires optimisation to successfully

balance these competing outcomes. Achieving this complex optimisation relies on architectural interventions—such as window design and shadings—which affect the energy balance by modulating envelope heat losses and filtering solar heat gains. On the one hand, insufficient provision compromises visual performance and psychological wellbeing while increasing electric lighting demand. On the other hand, excessive exposure detrimentally affects both the occupant—through visual glare and thermal stress—and the building’s energy balance, where the associated large glazing ratios exacerbate summer cooling loads and winter transmission losses.

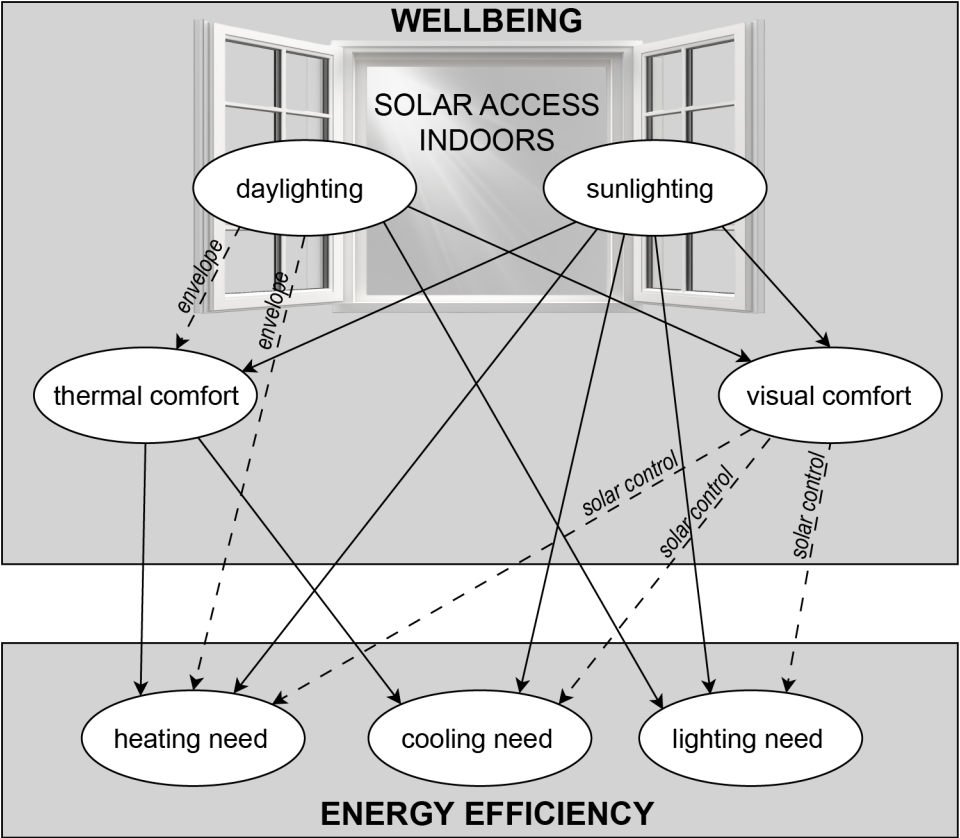


Figure 2
Conceptual framework illustrating the effects of indoor solar access on human wellbeing and building energy efficiency.

This doctoral thesis frames solar access specifically through the lens of habitability, anchoring its focus within the wellbeing domain of the conceptual framework (Figure 2). In the context of urban densification, the primary risk is an under-supply of solar access. Therefore, while acknowledging the risks and necessary mitigation

strategies associated with over-supply, this research concentrates on ensuring that urban form retains the geometric capacity to deliver sufficient daylight and sunlight to meet regulatory minimums for health and comfort.

2.2. A taxonomy of solar performance metrics (Paper I)

The field of solar access assessment encompasses numerous metrics that vary significantly in input complexity and computational demand. To navigate this landscape and identify metrics suitable for early-stage urban design, Paper I derived a taxonomic classification system through an integrative literature review. Relevant scientific literature was sourced from the Scopus database using core concept keywords encompassing solar access, metrics, and neighbourhoods. The identified metrics were analysed and categorised based on their required inputs, methods of formulation, communication formats, and primary functions. This analytical process yielded a taxonomy that organises solar metrics into four distinct levels of complexity based on their specific computational needs:

- *Geometrical Metrics (G)*: These metrics rely exclusively on the geometry of the urban form. They are static and independent of geographical location, orientation, and weather data. Their primary utility lies in their computational simplicity and their focus on the potential of the form itself. G-metrics include density indicators, such as FAR, but also sky-view metrics, such as VSC and SVF.
- *Latitudinal Metrics (L)*: These metrics feature information about the annual solar vectors corresponding to the site's latitude. While they incorporate the sun path and cardinal orientation, they assume a clear sky, effectively treating the sky vault as a geometric dome without local weather phenomena or cloud cover. The typical use of L-metrics involves sunlighting and overshadowing analysis.
- *External Climatic Metrics (EC)*: These metrics integrate local climate data (via Typical Meteorological Year files) to calculate solar performance on external surfaces. They account for the specific stochastic properties of the local sky throughout a year, including cloud probability. The most common metrics in this category involve solar irradiation.
- *Internal Climatic Metrics (IC)*: These metrics calculate climate-based performance within the building volume and often represent the highest regulatory standard. They require detailed inputs regarding, for instance, wall thickness, window size and placement, and material properties.

A primary methodological constraint driving this thesis is the incompatibility of IC-metrics with early urban planning stages. As outlined in the problem statement, the

specific architectural data required for IC simulations remain indeterminate during urban planning. Consequently, it was concluded from the review that simplified early-stage assessment requires the use of G-, L-, or EC-metrics as proxies.

2.3. Identifying solar access indicators for urban planning (Paper II)

Moving beyond simple density metrics is critical for early-stage solar access assessment. Traditional density metrics, particularly FAR, are inherently non-spatial; they quantify land use intensity but fail to describe the distribution of mass. To computationally test the efficacy of alternative form-based metrics and their relationship to density, Paper II employed a parametric simulation methodology. The study analysed two types of neighbourhood models: parametric iteration-based designs and real-world case studies from Malmö city districts. These models were based on three dominant Swedish residential typologies—courtyard, slab, and tower—and generated at Level of Detail 1 (LoD1, featuring flat roofs and no façade details). The iteration dataset utilised homogeneous 5x5 building cluster grids to generate over 3,000 unique permutations of geometry and orientation, featuring varying heights, side dimensions, and building offsets. Solar access metrics were simulated for the central building's façades and the surrounding ground surfaces using Ladybug Tools within Rhinoceros and Grasshopper. Subsequent statistical analyses, including Kendall rank correlation, were performed in RStudio to evaluate the strength of relationships between the urban form parameters and the resulting solar metrics.

Research conducted in Paper II reveals that the relationship between density and solar performance is heteroscedastic. While density governs the general trend, the variance in performance typically increases with higher urban density. For instance, at a Volume Area Ratio (VAR) of approximately 5 (calculated as building volume over plot area), the average VSC across different homogeneous designs ranged from 20% to 28% (Figure 3). This substantial span, which becomes even larger at higher densities, indicates that for the same density, the specific morphological configuration can substantially alter the available sky view. This demonstrates that density targets alone are insufficient for ensuring solar access.

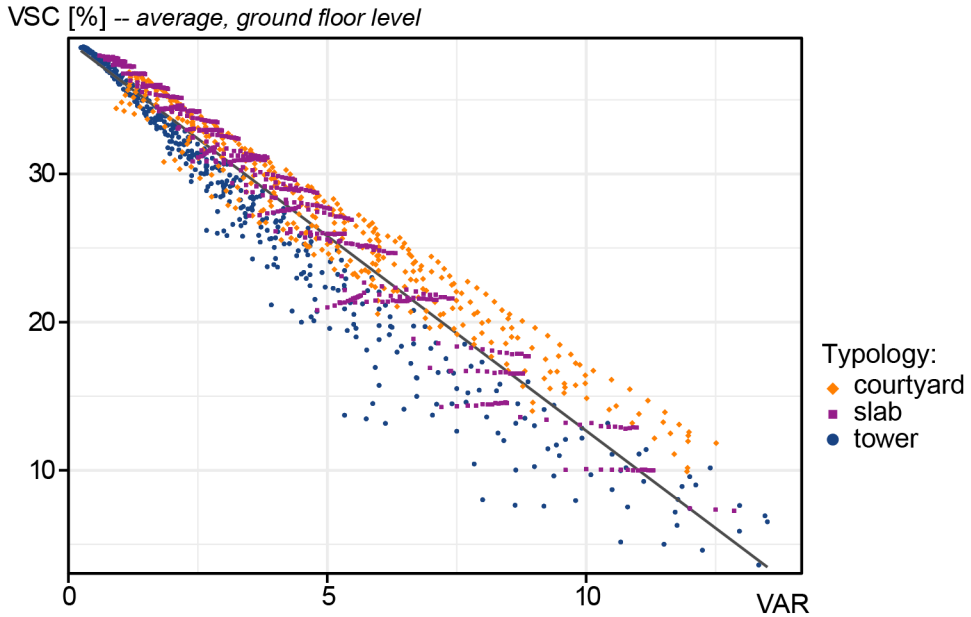


Figure 3

Relationship between average VSC (Vertical Sky Component, daylighting potential on façades) and VAR (Volume Area Ratio, urban density) based on parametric neighbourhood design iterations.

To align density more closely with volumetric obstruction, this research utilises VAR rather than FAR. While FAR remains useful for quantifying the economic and demographic aspects of urban density—determining rentable floor space and population capacity—it relates poorly to solar performance because it ignores building height. By contrast, VAR integrates the vertical dimension of the building masses, effectively eliminating the variable of storey height. This makes VAR a superior control variable for isolating the relationship between urban form and solar access, independent of the internal floor count.

For daylighting, this research adopts the VSC metric as the primary early-stage indicator for indoor potential. In the comparative analysis of Swedish neighbourhood typologies, VSC demonstrated an 85% correlation with urban density. VSC isolates the impact of external urban massing from internal architectural features. This makes it a simple, yet effective measure of the sky view available to a façade, independent of window dimensions or room depth. However, it is important to acknowledge the climatic limitations of this metric. Because VSC relies on the standard CIE overcast sky model, it is highly suitable for high-latitude contexts like Sweden where diffuse, cloudy conditions are common, but it may be less suited for geographical regions characterised by predominantly clear skies.

For sunlighting, the methodological approach must account for direct beam solar radiation. The availability of direct sunlight at a point in space can be reduced to a simple vector-based calculation, using Latitudinal (L) metrics. The research identified Annual Sunlight Hours (ASH) as the preferred indicator for assessing indoor sunlighting. Classified as an L-metric, ASH mirrors the geometric logic of the "Sunlight Exposure" metric defined in EN 17037 but expands the temporal scope from a single reference date (between February 1st and March 21st) to the full annual cycle. Paper II demonstrated that this annual approach yields, on average, an approximately 15% stronger statistical correlation with urban density and other G- and L-metrics compared to the Sunlight Hours on 21st of March (SH 21/3)—a single-day reference metric. Furthermore, the Kendall rank correlation between ASH and SH 21/3 was $\tau = 0.73$, suggesting that ASH provides a distinct temporal measure; by accounting for all annual daylight hours rather than a single 12-hour period, it achieves a higher level of granularity in assessing solar access.

Ultimately, Phase 1 provided a matrix of four primary solar access indicators (Table 2) that can be applied in the evaluation of the urban plans and early building designs: VSC and ASH for indoor daylighting and sunlighting (façade-based assessment), and SVF and SH 21/3 for outdoor daylighting and sunlighting (ground-based assessment). For clarity and consistency within this thesis, the metric evaluating equinox direct sunlight provision is referred to as SH 21/3, superseding the term 'Reference Day (RD) Sunlight Hours' used in the earlier appended paper (Paper II).

Table 2
The identified solar access indicators.

	Daylighting	Sunlighting
Indoors	Vertical Sky Component (VSC)	Annual Sunlight Hours (ASH)
Outdoors	Sky View Factor (SVF)	Sunlight Hours on 21 st March (SH 21/3)

While this broader framework acknowledges the importance of solar access in outdoor spaces, the subsequent operational chapter of this thesis (Chapter 3) focuses exclusively on the indoor metrics (VSC and ASH). This delimitation is driven by the regulatory gap identified in the problem statement: the need to pre-emptively address internal building compliance and residential habitability within the urban planning phase.

3. Operationalising metrics for urban planning

The theoretical framework presented in the previous chapter identified VSC and ASH as the most appropriate metrics for assessing indoor solar access at the urban scale. However, for these indicators to be robust in a regulatory context, they must be adjusted against the specific compliance standards they are intended to support or the occupant experiences they are presumed to reflect. This chapter presents the workflows and findings from Phase 2 and Phase 3 of the research design, addressing RQ2 and RQ3 respectively, which asked: *“How can the identified early indicator of indoor daylighting be calibrated to ensure compliance with regulatory standards?”* and *“How do quantitative indoor sunlighting metrics align with human perception and satisfaction in high-latitude residential contexts?”* It details the quantitative calibration of daylighting targets (Chapter 3.1) and the qualitative evaluation of sunlighting metrics against human perception (Chapter 3.2).

3.1. Bespoke targets for daylighting (Paper III)

Predicting regulatory compliance of buildings at the urban planning stage is methodologically complex; the DDP governs buildings’ volumetric limits while building regulations, such as the BBR and EN 17037, regulate their internal environmental quality. Consequently, final compliance depends on architectural variables, such as room layouts and window dimensions, that are determined long after the DDP is finalised. Lacking specific guidance, practitioners rely on heuristics, most notably the rule of thumb that $VSC \geq 27\%$ provides adequate indoor daylight. Paper III challenged the universality of this threshold and developed a computational workflow to generate bespoke VSC targets linked to room design parameters.

3.1.1. VSC calibration workflow

A parametric simulation study was designed to study the relationship between the degree of external obstruction (measured via VSC) and internal daylighting

performance (regulatory compliance). The methodology employed a standardised ‘shoebox’ model located on the ground floor, representing the ‘worst-case’ scenario for solar access in a multi-storey context, located at the lowest level of an urban canyon (Figure 4). This simplified geometry allowed for the isolation of specific morphological variables, removing the confounding influence of complex architectural layouts.

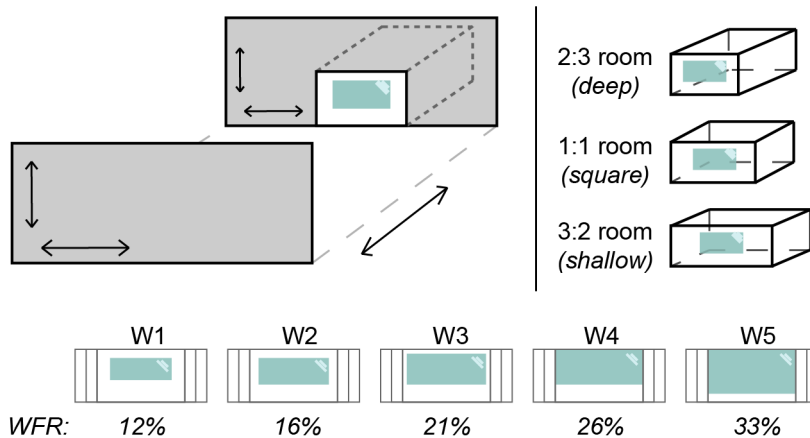


Figure 4

A schematic diagram illustrating the parametric "shoebox" setup for the VSC metric (Vertical Sky Component) and daylight compliance simulations, showing the variable room ratios, window designs (W1-W5) with their Window-to-Floor-Ratios (WFR), and the parametric external obstruction plane. Figure adapted from Paper III.

The simulation script was constructed around three primary geometrical variations (Figure 4):

1. *Room geometry:* Three distinct room width-to-depth ratios were tested (2:3, 1:1, and 3:2) to represent varying plan dimensions, while maintaining a constant floor area and ceiling height.
2. *Window size:* Five window sizes (glazing only) of typical clear glass properties were simulated. To quantify the level of glazing, the study used WFR over the traditional WWR. WFR provides a stronger correlation for spatial daylighting analysis as it links the aperture size directly to the floor area being illuminated, rather than the surface area of the façade.
3. *External obstruction:* To simulate the shading effects of an external obstruction by a neighbouring building block, a vertical opaque plane was placed parallel to the window. By incrementally varying the height, width, and distance of this obstruction, the study generated 490 unique obstruction scenarios, resulting in a VSC dataset ranging from 2% to 38% at the centre of the window.

To contextualise the study's use of net glazing-based WFRs, Figure 5 maps these values onto a physical façade using framed WWRs. For a standard 2.5 m high square room, the figure assumes a 0.1 m frame, 0.2 m separating walls, and a 0.45 m floor slab. This illustrates the deceptive nature of the WWR metric; for instance, with a 50% WWR, the window seems to dominate the façade proportion when in fact it covers exactly half of the total surface area.

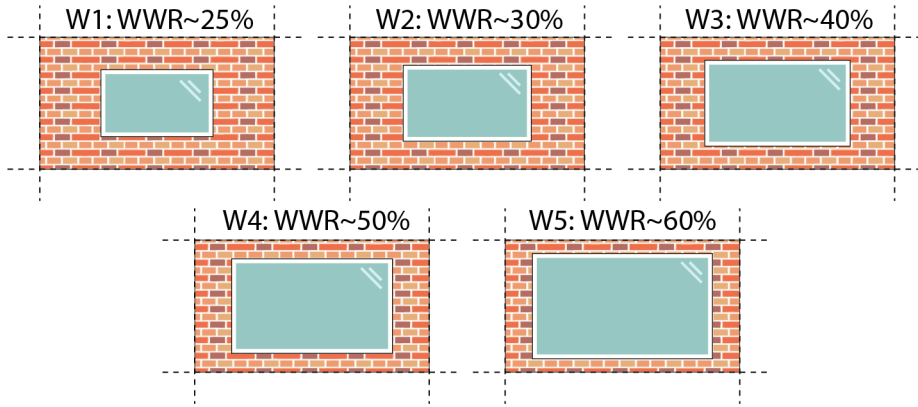


Figure 5

Translation of the simulated window sizes into external Window-to-Wall Ratios (WWR) for the square 1:1 room. This figure is for illustrative purposes only to demonstrate external visual scale; while the total glazing areas correspond to the study, the specific window dimensions and their placement on the façade do not strictly follow the simulation models.

For each of the 490 obstruction scenarios, internal daylight performance was simulated using Radiance-based tools (Ladybug/Honeybee). The performance was assessed against two regulatory frameworks: the Swedish BBR requirement (using Point Daylight Factor $\geq 1\%$ of the superseded BFS 2011:6) and the European standard EN 17037 (assessed via both the Daylight Factor method and the climate-based Illuminance method using Copenhagen weather data).

The calibration process employed a probabilistic approach to define the targets. A compliance threshold of 95% was applied, meaning a VSC integer was accepted as a valid target only if at least 95% of the simulated cases within that 1% interval met the internal regulatory requirements. This threshold was selected to align with standard statistical conventions (i.e., the 95% confidence interval). Consequently, the resulting targets aim to provide a high probability of compliance, acknowledging the inherent uncertainty of early-stage planning without claiming absolute predictability.

3.1.2. VSC calibration results and practical implications

The results of the calibration process, validated via Receiver Operating Characteristic (ROC) analysis, confirmed that VSC is an “excellent” predictor of internal daylighting compliance according to the statistical method used ($AUC > 0.9$). The analysis also exposed the inadequacy of a single, universal VSC target.

The widely cited 27% VSC benchmark proved to be valid only under specific, less demanding conditions, primarily for meeting the Swedish BBR requirement with moderate to high glazing ratios and shallow rooms (Figure 6). For instance, a square room with a conventional 30% WWR (see Figure 5) is likely to fail BBR compliance in the architectural phase if the façade target is set to 27% VSC during early planning. When tested against the stricter EN 17037 recommendations, the 27% threshold was often insufficient unless paired with large apertures and shallow rooms (Figure 7).

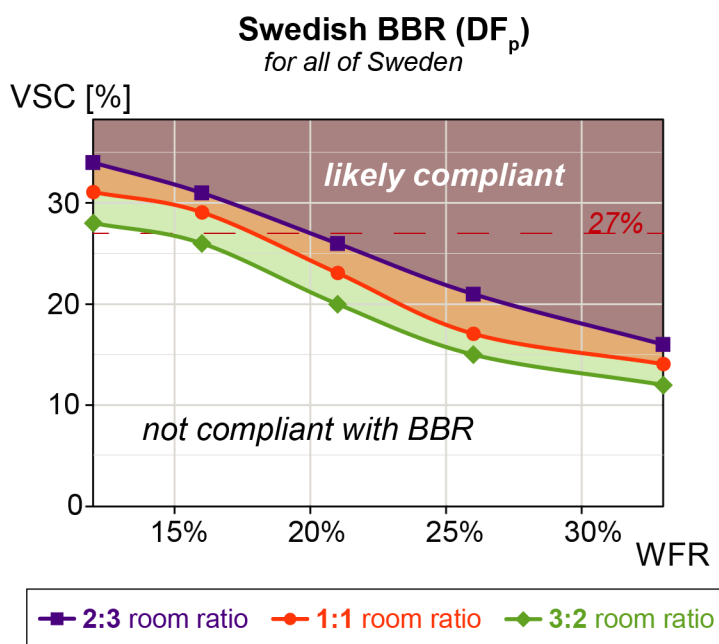


Figure 6

VSC (Vertical Sky Component) targets for daylighting compliance with the Swedish building regulations (BBR, BFS 2011:6—superseded) based on WFR (window-to-floor area ratio) and room ratio (width-to-depth ratio). The compliance charts apply for any orientation and any location in Sweden.

EN 17037 (by illum.) for Copenhagen, Malmö

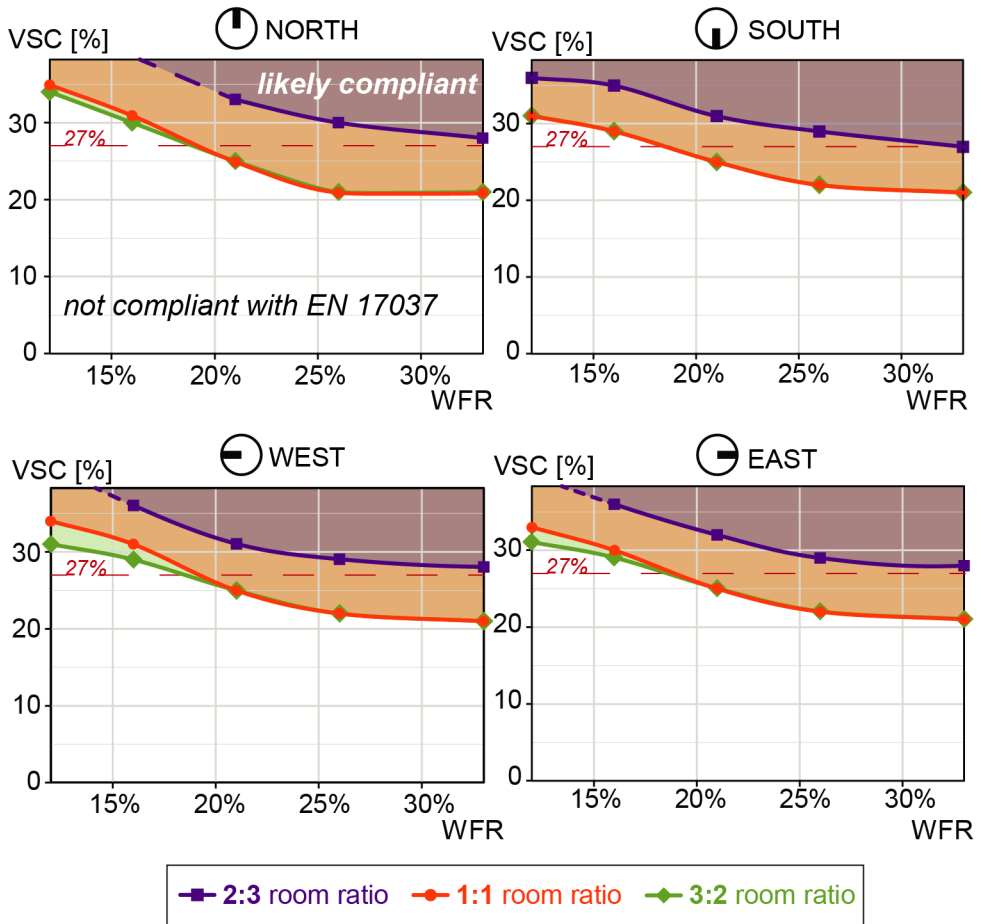


Figure 7

VSC (Vertical Sky Component) targets for daylighting compliance with the EN 17037 minimum illuminance daylighting level based on WFR (window-to-floor area ratio), room ratio (width-to-depth ratio), and window orientation. The compliance charts apply for the Copenhagen (DK) and Malmö (SE) location and climate contexts.

The significant contribution of Phase 2 is not a single universal threshold, but rather a matrix of bespoke targets. The workflow demonstrates that the required VSC is inextricably linked to the WFR and the room geometry. Shallow rooms were found to be less sensitive to the degree of external obstruction, requiring lower VSC values to maintain compliance than deep rooms.

To account for this variability, this thesis advocates replacing the static universal threshold with geometry-dependent target values directly linked to regulatory

compliance. By specifying an expected WFR and room typology, planners can use the derived compliance curves to define precise VSC targets for proposed developments. Inversely, this logic facilitates the early identification of architectural constraints. Once urban massing is defined and façade VSC levels are calculated, the maximum permissible room depths or required window sizes can be mathematically derived. For example, mapping the minimum WWR required across a façade (Figure 8) provides a direct spatial visualisation of these geometric constraints.

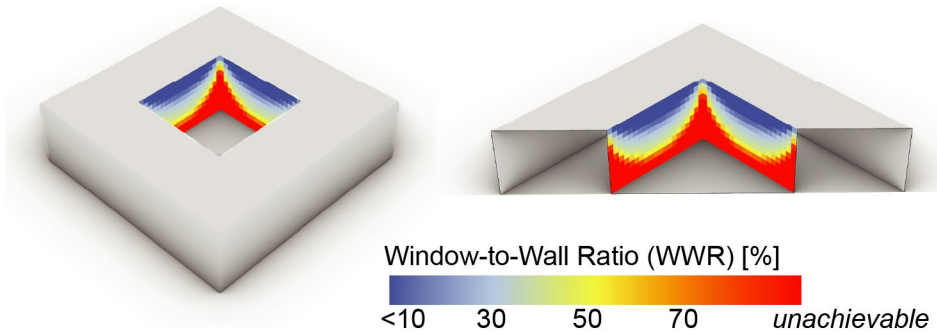


Figure 8
Minimum Window-to-Wall Ratios (WWR) required for EN 17037 daylight compliance (the illuminance method). The thresholds were derived from Vertical Sky Component (VSC) simulations, assuming a square (1:1) internal room ratio. Source: Paper III.

3.2. Human perception of sunlighting (Papers IV & V)

A knowledge gap exists regarding the relationship between measured quantities of direct sunlight in residential spaces and the resulting perception and satisfaction of building occupants. Current standards, such as EN 17037, operate on a logic of scarcity by prescribing minimum targets designed to prevent solar deprivation. However, this approach often overlooks the complex dynamic of solar exposure. Papers IV and V were conducted to investigate this gap: specifically, Paper V established an empirical baseline of occupant attitudes toward sunlight, while Paper IV evaluated the extent to which current provision-based metrics reflect those residential preferences.

3.2.1. Methodological approach

To bridge this gap, the research employed a mixed-methods design that triangulated simulated solar exposure with quantitative and qualitative occupant evaluations. By pairing in situ interviews and surveys with simulated sunlight exposure (ASH and SH 21/3) of the same apartment room, the study could directly compare the calculated metric with the occupant's specific appraisal of that space. This qualitative investigation was subsequently contextualised within broader attitudes through a national online survey, "Sunlight Home", exploring how local findings align with the preferences of a wider population.

3.2.2. Integrating metrics with perceptions

To directly evaluate the EN 17037 framework, the qualitative findings from 10 in situ interviews were compared against the simulated metric performance of the visited apartments ($n = 7$). Because the evaluated rooms scored either below the EN 17037 "minimum" or above the "high" sunlight exposure levels, the comparison revealed how residents experience and navigate indoor sunlight conditions at the extremes of the regulatory spectrum:

- *Rooms below the "minimum" standard (IDs 2, 5, 7):* Objective sunlight scarcity broadly aligned with underlying dissatisfaction. However, quantitative survey ratings sometimes obscured this deficit due to occupant adaptation. The interviews revealed that residents rated their sunlight as "enough" because they felt compensated by access to outdoor gardens and other environmental benefits; they accepted the sunlight scarcity in the room as a fair trade-off for cooler summer temperatures or lack of screen glare—despite expressing a latent desire for brighter living spaces.
- *Rooms exceeding the "high" standard (IDs 1, 3, 4, 6):* Abundant geometric direct sunlight provision from simulations aligned with satisfaction with the

sunlighting in the rooms, particularly when complemented by effective glare mitigation. A critical paradox emerged in Apartment 4: while the room received a high level of sunlight exposure, it failed to meet minimum diffuse daylight standards (assessed using the VSC method from Chapter 3.1). As a result, when residents drew the blinds to block the glare, they exacerbated the underlying lack of diffuse daylight from the sky, leaving the room uncomfortably dark.

3.2.3. The duality of solar exposure

The analysis of the qualitative investigation revealed a distinct duality in the experience of indoor sunlighting. Residents consistently identified direct sunlight as a source of psychological wellbeing, citing benefits related to mood enhancement, circadian regulation, and a sense of connection to the outdoors. However, this positive appraisal was countered by the experience of sunlight as an environmental stressor, manifesting primarily as screen glare and summer thermal discomfort. Consequently, the relationship between quantitative sunlight access and occupant satisfaction was found to be conditional; higher values of direct sunlight provision did not directly equate to higher satisfaction if the associated negative effects were not mitigated.

The study suggests that satisfaction is determined less by the absolute provision of sunlighting and more by the manageability of the environment. In apartments where metrics indicated high direct sunlight access, satisfaction was largely contingent on the availability of effective coping resources, such as adjustable shading. In cases where high sunlighting levels were paired with inadequate control mechanisms, the resource became a liability, leading to complaints of "blinding" glare and overheating.

Despite this complexity, the study found empirical support for the relevance of minimum sunlighting thresholds. Residents in apartments that fell below the EN 17037 recommendation (receiving less than 1.5 hours of sunlight on March 21st) expressed distinct dissatisfaction or a sense of resignation, tempered by the relief that they were not subject to the overheating common in higher-level units. This suggests that while threshold-based metrics cannot guarantee satisfaction (which requires control), they identify environments at risk of solar deprivation.

3.2.4. Preferences and design implications

The findings provided evidence of distinct cultural and spatial preferences governing where and when sunlight is desired. Notably, residents prioritised solar access in living rooms above all other spaces. Survey results indicated a specific preference for afternoon sunlight in the living rooms and morning sunlight in

kitchens—patterns that closely align with self-reported occupancy rhythms. A notable cultural divergence emerged regarding bedrooms: respondents of Swedish origin were significantly more likely to reject direct sunlight in these spaces compared to non-Swedish respondents, likely driven by the adaptive need to maintain sleep hygiene during the long photoperiods of the Nordic summer. Collectively, these temporal and spatial preferences for direct sunlight access established the basis for residential window orientation guidelines. Figure 9 outlines these recommendations for the three most common room types.

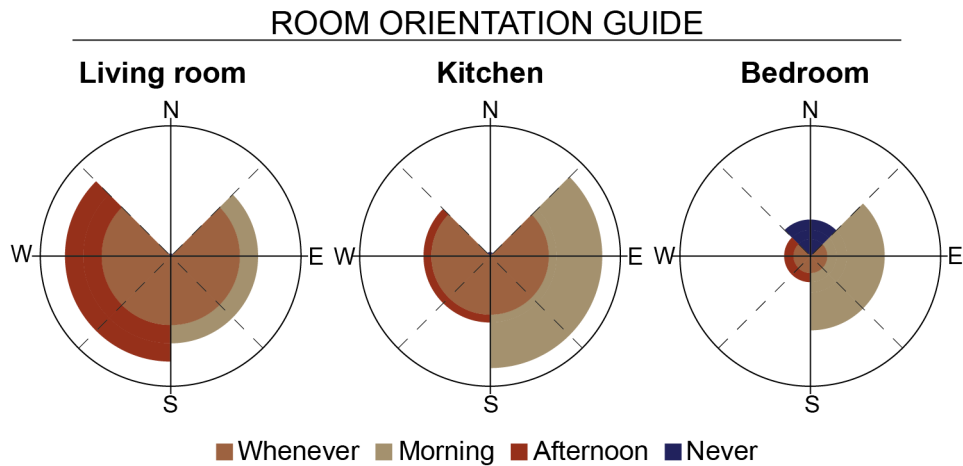


Figure 9
Room orientation guide as an interpretation of the survey preferences regarding time-of-day direct sunlight access: morning (NE–S), afternoon (S–NW), whenever (NE-S-NW), and never (NW-NE). The size of the category is relative to the frequency of survey responses; full circle (centre to edge) = 100% respondents. ‘Whenever’ responses are compiled with ‘Morning’ / ‘Afternoon’. Source: Paper IV.

Ultimately, the findings expose the gap between theoretical solar access and the actual habitability of a space. While minimum sunlight duration targets (e.g., SH 21/3) establish a necessary baseline for solar potential, the study concludes that they cannot, on their own, guarantee occupant satisfaction. For residents to enjoy the benefits of the sun without the associated discomfort, the findings demonstrate that occupant control and agency are required. Resolving the conflict between the psychological desire for natural light and the physical need for comfort therefore relies on treating adjustable shading as a fundamental building component.

4. Discussion

This chapter discusses the core findings of the thesis by systematically addressing each of the three RQs. Furthermore, it presents the broader implications of solar provision within the current regulatory landscape, acknowledges the methodological limitations of the study, and outlines actionable trajectories for future research.

4.1. Identifying solar access indicators (RQ1)

Which simple metrics can be used as indicators of solar access (sunlighting and daylighting) in the assessment of early-stage urban plans and building designs?

Addressing RQ1, this research identified four primary solar access indicators for early-stage assessment. For indoor potential (façade-based), the Vertical Sky Component (VSC) and Annual Sunlight Hours (ASH) were selected for daylighting and sunlighting, respectively. For outdoor public spaces (ground-based), the Sky View Factor (SVF) and Sunlight Hours on 21st March (SH 21/3) serve as the corresponding metrics. To maintain computational efficiency at the DDP stage, the daylighting indicators utilise Geometrical (G) metrics, whereas sunlighting relies on Latitudinal (L) metrics to capture the orientational dependency of direct solar radiation.

Evaluating daylighting exclusively through G-metrics inherently assumes an isotropic sky, omitting the orientational nature of real-world solar distribution. However, this methodological abstraction aligns directly with the compliance structure of the Swedish regulations. The BBR assesses daylighting using the DF – a G-metric based on the standard CIE overcast sky model. While this legal framework justifies the use of VSC as an early-stage proxy, other, more refined compliance assessments based on CBDM may require combining G- and L-metrics to formulate a single, orientation-responsive indicator.

Although solar access indicators were identified for both domains—indoor and outdoor—the operational phases of this research focused exclusively on indoor metrics. This delimitation reflects the broader regulatory landscape: indoor solar access (especially daylighting) is governed by strict compliance thresholds, whereas

prescriptions for outdoor environments typically lack standardised targets, largely because the specific quantitative needs for outdoor exposure remain undefined. This prioritisation does not intend to lower the significance of outdoor solar access. Rather, evaluating the outdoor environment necessitates an integrated approach, in which solar access is assessed concurrently with wind flow and thermal analyses to accurately map outdoor comfort and the urban heat island effect. While optimising building spacing to meet indoor daylighting standards might indirectly ensure adequate outdoor solar access, this spatial relationship lacks empirical validation and requires future research.

Findings from Paper II demonstrate that urban morphology acts as a critical mediator between density and solar potential. Parametric analyses of homogeneous neighbourhoods revealed that at equivalent densities, certain typologies yield higher solar access results. However, translating these morphological findings directly into planning policy requires caution. Evaluating typologies solely through the lens of solar access risks a deterministic approach to urban design. Solar performance is merely one variable within a multi-objective domain. For instance, while towers maximise façade sunlight, they can simultaneously generate adverse wind microclimates at the pedestrian level and reduce urban enclosure (Blocken & Carmeliet, 2004; Gehl, 2010). Therefore, the identified early-stage solar indicators should not be used to unilaterally optimise massing. Instead, they should be integrated into a holistic evaluation framework that balances environmental performance with perceived safety, streetscape attractiveness, and socioeconomic vitality of a neighbourhood.

4.2. Calibrating targets for compliance (RQ2)

How can the identified early indicator of indoor daylighting be calibrated to ensure compliance with regulatory standards?

Having identified VSC as a viable early-stage indicator, answering RQ2 required calibrating the metric to generate targets that align with daylighting regulations. Paper III achieved this by investigating the efficacy of VSC in assessing compliance with daylighting standards, specifically the Swedish BBR and the European standard EN 17037.

To determine reliable VSC thresholds for these regulatory requirements, the research developed a method for selecting the compliance level utilising a statistical 95% confidence level. For the BBR, which relies on the geographically independent DF, the bespoke VSC targets derived from this method may be applied universally across Sweden to assess early massing designs. Although the BBR version used in this study has since been superseded by BFS 2024:8 (see Table 1), these findings

establish a methodological baseline that is readily adaptable to the new regulatory context. In contrast, the targets calibrated for EN 17037 are climatically bound, specifically representing the Copenhagen and Malmö geographical contexts. Additionally, as the results provide discrete VSC targets for the cardinal directions, assessing intermediate orientations requires interpolating these values.

Methodologically, the simulations for this calibration were based on parametric bins rather than continuous data, and the geometric variations in the assessed designs were purposefully limited to typical configurations. To further verify and expand upon this method, future iterations should process a larger dataset with continuous parameters, encompassing a broader spectrum of architectural designs.

Despite providing a compliance-driven targets, this early assessment method presents practical implementation challenges. It requires urban planners to prepare 3D models and conduct active VSC simulations—a potential technical hurdle for practitioners accustomed to simpler methods, such as one-click overshadowing tools or obstruction angle calculations (Kanters et al., 2021). Furthermore, the VSC metric itself can be abstract for non-specialists. To improve practical comprehension, the assessment workflow can be adapted to translate the initial VSC simulation results into a required WWR for the corresponding façade (see Figure 8). This conceptual translation offers immediate, intuitive feedback: if the recommended WWR required to meet daylight compliance exceeds 100%, the target is physically impossible. Such a result indicates that the proposed urban massing must be modified to allow for a greater sky view.

4.3. Aligning with human perception (RQ3)

How do quantitative indoor sunlighting metrics align with human perception and satisfaction in high-latitude residential contexts?

In the preceding phase, the early-stage daylighting indicator (VSC) could be calibrated against existing compliance targets because daylighting research and its associated regulatory frameworks are extensive and well-established (Jin et al., 2025; Vikberg et al., 2022). Yet, current standards for indoor sunlighting lack a comparable foundation of modern empirical evidence across European contexts. Consequently, answering RQ3 required evaluating how the quantitative provision of indoor sunlight—assessed via ASH and SH 21/3—aligns with human perception and satisfaction in high-latitude Swedish contexts.

The empirical findings reveal that while objective geometric thresholds, such as the EN 17037 minimums, are relevant indicators of baseline habitability, the relationship between quantitative metrics and human perception is complex. This alignment is mediated by psychological adaptation to sunlight scarcity and

conscious environmental trade-offs. For dwellings falling below the minimum thresholds, objective solar scarcity generally aligns with underlying dissatisfaction. However, the data highlights that occupants adopt coping mechanisms. By valuing secondary benefits—such as a cooler summer environment—most residents evaluated suboptimal indoor solar access as "enough." Consequently, simple quantitative rating scales can be misleading as they may fail to capture when occupants have lowered their expectations over time. This research demonstrates that deeper qualitative inquiry is necessary to uncover the nuances of occupant satisfaction.

Furthermore, the experience in dwellings that meet or exceed the EN 17037 “high” sunlight exposure standard illustrates the inherent risks of excess. Abundant provision aligns with high satisfaction only when occupants possess effective means to mitigate glare and solar heat gains. This serves as a reminder that standards focusing solely on minimum provision fail to address the negative impacts of overexposure.

4.4. Solar provision and control

To bridge the gap between abstract sunlighting metrics and habitable reality, the assessment of indoor solar access is best addressed through two complementary design elements: geometric potential and user control.

Solar provision is defined at the intersection of the urban plan and the architectural layout. While north-facing façades are unavoidable in urban plans, internal space plans should ensure no dwelling is exclusively oriented towards this sector (NW-NE), ensuring that every unit has a theoretical potential for direct sunlight exposure. Furthermore, the provision of private outdoor spaces, such as balconies, can satisfy the psychological desire for direct sunlight. Balconies also function as overhang solar shadings that block excessive high-angle summer radiation while admitting the low-angle winter sun. However, the contemporary trend of designing larger, deeper, and more numerous balconies (White arkitektur AB, 2019) must be carefully managed to prevent these structures from obstructing too much diffuse daylight.

As the empirical data demonstrates, geometric potential for solar access alone is insufficient. Modern densification strategies often pair tighter, highly insulated buildings with increased glazing ratios to meet mandatory daylight compliance. This introduces a critical conflict: larger windows are required to secure necessary diffuse daylight, but they may simultaneously increase the admission of direct solar radiation leading to overheating and glare. Because occupant satisfaction is contingent not merely on the quantitative presence of sunlight but on the ability to modulate it, the provision of effective shading systems should not be left entirely to the end-user, but rather integrated into the architectural design.

For the residential sector, the findings challenge the current office-oriented approach of standards such as EN 17037, where shading requirements are often contingent on simulated glare probability. Instead, the empirical data suggests that adjustable shading be required for any residential room receiving direct sunlight. Guidelines should prioritise systems that decouple glare protection from total daylight and view exclusion—such as Venetian blinds or adjustable louvres—rather than binary (open/closed) solutions. Relying on occupants to retrofit these solar control systems is inequitable, particularly in the rental sector, where tenants lack the authority to modify the façade or the financial incentive to invest in integrated bespoke shading solutions. Furthermore, treating solar control as a post-occupancy afterthought may result in ad-hoc interior installations that compromise both the functional performance and the intended architectural expression of the façade (Kuhn, 2017). To guarantee long-term habitability and psychological well-being, adjustable shading should be considered a fundamental component of the building design rather than an optional addition.

4.5. The regulatory landscape

Recent revisions to the BBR mark a significant shift in the status of solar access in Sweden (Boverket, 2024). By removing the prescriptive requirement for direct sunlight access and retaining only mandates for diffuse daylight provision and outlook, the choice to provide direct sunlight has consequently been transferred to property developers, leaving architects to advocate for sunlighting without a regulatory leverage. This deregulation introduces a risk: without explicit protections in the building code, sunlighting may evolve from a guaranteed standard into a market commodity. Consequently, urban access to direct sunlight risks becoming a privilege defined by purchasing power rather than fundamental occupant needs (Fleming et al., 2018).

In the absence of mandatory national sunlighting minimums, securing solar access in densified cities relies on the voluntary adoption of analysis frameworks like EN 17037 and early-stage metrics (such as VSC and ASH). Urban planners can drive this process by embedding quantitative assessments directly into the DDP phase, thereby minimising severe overshadowing and promoting equitable urban environments.

4.6. Methodological limitations

Any digital representation of the built environment is inherently subject to granularity limitations, particularly when employing simplified metrics and low-detail models. Consequently, the simulated outputs in this thesis represent a baseline geometric capacity rather than a precise prediction of finalised architectural performance.

In Phase 1 (definition and identification), parametric evaluations relied on homogeneous neighbourhood designs. Resulting metrics were calculated as aggregated averages, obscuring localised variations. Furthermore, micro-scale environmental features that impact real-world solar access, such as vegetation, were excluded.

During Phase 2 (calibration), the simulation model was abstracted to a single-aspect "shoebox" room with one centrally positioned window. The external obstruction was modelled as a symmetrical, perpendicular plane, which does not reflect the irregularities of real urban plans. Additionally, the data extracted for calibration was bin-based rather than continuous, introducing discretisation into the threshold boundaries.

The reliance on static sky models introduces a climatic limitation. By adopting the VSC as a primary early-stage indicator, the methodology relies on the standard CIE overcast sky model. While representative of high-latitude, diffuse-sky-dominated environments and aligned with Swedish compliance methods, it does not capture the dynamic variability of cloud cover, luminous efficacy, or direct sunlight contributions that Climate-Based Daylight Modelling (CBDM) would register.

The VSC thresholds derived in this thesis are calibrated specifically to the preceding BBR framework. Although the newly enacted BFS 2024:8 retains the 1% DF target, it introduces modifications to the assessment method (see Table 1). Because it is uncertain if these modifications shift the corresponding VSC targets, the entire calibration process should be repeated to validate the targets against the updated code.

In Phase 3 (evaluation), the qualitative investigations present geographic and statistical constraints. The in situ interviews were restricted to a small sample localised entirely to southern Sweden; given the country's extensive latitudinal range, this limits the nationwide generalisability of specific sunlighting preferences. Furthermore, the in situ sample size is insufficient to robustly validate or update sunlighting thresholds in accordance with human perception. Concurrently, the large-scale public survey utilised a convenience sample, which means that the results may not be representative of the broader population.

4.7. Methodological scalability

Future research should aim to expand the methodology of bespoke EN 17037-based VSC targets to other European locations to verify its broader applicability. However, while this thesis calibrates geometric targets using a probabilistic approach, the methodology highlights the computational limits of simulation-based planning. Since the proposed method relies on deriving thresholds from specific climatic data, applying this workflow to generate corresponding VSC targets for different latitudes or municipalities requires replicating a computationally intensive simulation process. This overhead could limit broad municipal adoption. To bridge this gap, future research should transition from repetitive simulation to surrogate modelling or machine learning. By training algorithms on large datasets, it is possible to create predictive tools capable of estimating compliance thresholds for any specific location or urban morphology in real-time, thereby bypassing the need for computationally intensive workflows when developing local standards.

Furthermore, while this research identifies key trends in residential preference regarding indoor sunlighting, the sample size was insufficient to validate specific numeric thresholds for ASH or propose definitive new metrics. To evolve from general "rules of thumb" to evidence-based policy, it is necessary to scale up the qualitative sunlight survey across a larger sample of apartments. Future studies should correlate simulated sunlighting of these apartments with longitudinal occupant surveys to establish a statistical link between metric values and occupant satisfaction. Future qualitative surveys should be explicitly designed to account for psychological adaptation. As this research demonstrates, occupants may rate suboptimal solar access as "enough" simply because they have accepted the deficit and rationalised it through positive environmental compensations. Because this thesis indicates that sunlight preference has cultural dependencies, such expanded validation is required to determine whether current European prescriptions remain valid in the local Swedish context.

4.8. Future work

To advance the core findings of this thesis into broader practice, future research should build upon the scalability pathways outlined in Chapter 4.7 through three distinct trajectories:

1. The simulation database should be expanded to develop bespoke VSC targets across other European contexts under EN 17037, while existing Swedish BBR targets require recalibration to align with the updated assessment methodology of BFS 2024:8.
2. The qualitative sunlighting evaluations should be scaled to establish a statistically robust relationship between the indoor sunlighting metric (e.g., ASH) and perceived satisfaction with indoor sunlighting, aiming to derive minimum indoor sunlighting thresholds for the Swedish context.
3. Further qualitative investigations, such as interviews with urban planners, are needed to explore the operational challenges and opportunities of integrating VSC and ASH as early-stage solar access indicators directly into the Swedish municipal planning process and the formulation of the DDP.

5. Conclusions

This thesis demonstrates that neighbourhood morphology defined during early-stage urban planning determines the urban solar access and subsequent habitability of residential buildings. Prioritising occupant wellbeing over strict energy optimisation, this research provides an analytical framework that integrates solar access into the broader context of social sustainability. To evaluate urban designs effectively, workflows need to be adapted to the low level of detail available at the early design stages. Consequently, this study identified four specific early-stage indicators for evaluating both indoor and outdoor daylighting and sunlighting. For indoor environments, the Vertical Sky Component (VSC) and Annual Sunlight Hours (ASH) were chosen as the primary metrics to assess façade-based solar access.

This research showed that relying on the ubiquitous 27% VSC threshold during urban planning may compromise daylighting compliance in the subsequent architectural and building permit phase. To resolve this, the daylighting indicator (VSC) was statistically calibrated based on daylighting standards to facilitate compliance in subsequent architectural phases. This new method derives bespoke façade VSC targets, which are conditionally dependent upon internal room proportions, window-to-floor ratios, and façade orientations. By applying these calibrated thresholds, urban planners can foresee whether a proposed massing may necessitate higher glazing areas to secure late-stage compliance with the Swedish building code (BBR, BFS 2011:6) and the European standard (EN 17037). To operationalise this finding, it is recommended that early-stage design practices—including digital urban planning tools—replace the static VSC threshold with a matrix of geometry-dependent, compliance-based VSC targets.

While daylighting compliance relies on established quantitative frameworks, evaluating indoor sunlighting required aligning physical metrics with human perception. Qualitative evaluations in the Swedish context demonstrated a strong occupant preference for direct indoor sunlight, alongside complex psychological adaptation to quantifiable solar scarcity. Concurrently, the research revealed self-reported concerns associated with excess indoor insolation, specifically the resulting overheating and glare.

Driven by the empirical findings and the recent deregulation of prescriptive sunlighting targets in the Swedish building code, this research outlines empirical

recommendations related to direct sunlight provision indoors. First, to ensure a baseline of habitability, the study proposes a minimum regulatory mandate: a prohibition of single-aspect dwellings where all windows face exclusively north. Second, to mitigate the risks linked to excessive insolation, the study advocates for a mandatory integration of adequate solar control systems in all new developments. Finally, to support human-centric spatial design, the research provides specific room orientation guidelines aligned with occupant preferences.

Ultimately, this thesis delivers three primary contributions:

1. Empirically derived recommendations for the use of specific, LoD-appropriate metrics in early-stage solar access assessments.
2. Bespoke VSC targets for daylighting compliance, conditionally dependent upon contextual and architectural design parameters.
3. Empirical data demonstrating the critical role of planned sunlighting and integrated solar control in residential dwellings.

This research demonstrates how early-stage urban massing defines the availability of solar access, impacting the habitability and regulatory compliance of future buildings. The calibrated daylighting targets and empirical sunlighting guidelines provide a framework for evaluating initial massing and securing equitable solar access. However, practical implementation of these guidelines relies on their integration into urban planning paradigms and regulatory frameworks. Practitioners may adopt the bespoke daylighting targets to improve early-stage assessments and facilitate late-stage compliance. Furthermore, while indoor sunlighting is no longer prescriptively mandated, the empirical evidence of occupant preference equips architects and planners with the rationale to advocate for direct sunlight provision as a fundamental design prerequisite. To advance this human-centric approach, future research should focus on establishing an empirically grounded baseline for indoor sunlighting thresholds.

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