Impact of Street Orientation, Street Width and Building Height on Sunlight and Daylight Access in Swedish Urban Blocks

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Master Thesis in Energy-efficient and Environmental Building Design
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Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

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The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Abstract

Urban form strongly influences sunlight access, a critical factor for well-being in Nordic cities where low solar altitude and short winter days limit natural light. Despite its importance, solar access is often secondary in planning, as street layouts are typically shaped by topography, traffic, and existing infrastructure. Although analytical tools and historical examples highlight deliberate orientation strategies, there remains limited quantitative evidence on how street orientation directly affects daylight availability. This study develops simulation-based analyses to evaluate how street orientation influences sunlight access and diffuse daylight access in residential settings, using climate data from Lund, Stockholm, and Luleå to support early-stage urban planning guidelines for Nordic contexts.

The methodology combines qualitative and quantitative approaches. A literature and regulatory review is conducted to examine Nordic planning frameworks, including Boverket guidelines and EN 17037, in order to assess requirements for access to natural light and to position the study within the broader body of research on urban form and daylighting in high-latitude regions. Computer-based three-dimensional parametric urban models of simplified Nordic Street geometries are developed in Rhino/Grasshopper. These models incorporate a courtyard building typology representing an enclosed, inward-facing urban form that is common within the Nordic urban fabric, while street orientation is systematically rotated from 0° to 90°. Climate-based annual daylight and sunlight simulations are performed using typical meteorological year climate files for Lund, Stockholm, and Luleå. The key performance metrics include Direct Solar Hours, Annual Sunlight Exposure (ASE), Spatial Daylight Autonomy (sDA), Useful Daylight Illuminance (UDI), and Average Illuminance.

The findings indicate that street orientation has only a minor influence on daylight performance in courtyard buildings, with small differences observed between orientations. Building height and street width prove to be considerably more significant. Taller buildings reduce daylight at lower floors while increasing sunlight exposure at upper floors, and narrower canyon widths further worsen overall daylight conditions. Clear performance differences between cities are also evident, with higher latitude locations consistently showing lower daylight levels.

Taken together, the results suggest that daylight performance in Nordic courtyard buildings is primarily governed by urban geometry rather than orientation. Building height, street width, and latitude are therefore the most critical considerations in early-stage design. These findings provide a practical basis for improving daylight access in residential planning across Nordic cities.

Preface

Our background in architecture, combined with graduate studies in energy-efficient and environmentally responsible building design, formed the foundation for this research. Beyond academic training, both authors share a personal interest in urban design and planning - in how cities are structured, how streets are laid out, and how these decisions affect the quality of life of residents. One author pursued this interest at the undergraduate level, completing a thesis on urban design, which provided early exposure to the relationship between spatial planning and the built environment. The other author's undergraduate thesis focused on daylighting in a public building, offering a complementary perspective on how the physical environment shapes human experience. These shared interests and academic backgrounds naturally directed this research toward the intersection of urban form and building performance.

A particular motivation throughout our studies has been the role of natural light as a sustainable resource. Daylight, when properly considered in design, reduces dependence on artificial lighting, making it not only a comfort factor but a meaningful contributor to building energy efficiency. Beyond energy, we find it equally compelling how daylight directly influences the human circadian system in regulating sleep, alertness, and overall wellbeing. In regions where daylight is limited for significant parts of the year, this connection between access to natural light and human health makes the topic feel even more important to study carefully. This perspective, that natural light is simultaneously a free environmental resource and a biological necessity, runs through the core of this work.

Studying at a Nordic institution has played a direct role in shaping the direction of this research. Being based in this region made it natural to turn our attention toward the specific challenges and opportunities that Nordic cities present. The long winters, low solar altitudes, and strong seasonal contrast in daylight are not abstract concepts here, they are part of everyday experience. At the same time, the Nordic region is at the forefront of sustainable urban development, with a growing commitment to energy efficiency, climate-responsive design, and high environmental standards. Seeing this shift happen around us made the research feel both relevant and timely. The region also offers reliable climate datasets and well-established daylight standards, providing a solid foundation for simulation-based research.

Finally, AI-based language tools were used during the writing process of this report to assist with paraphrasing and improving the clarity of the text. All academic content, arguments, and interpretations remain entirely the work of the authors.

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Table of Contents

List of abbreviations

APS	Area of Permanent Shadow
ASE	Annual Sunlight Exposure (%)
BBR	Boverket Building Regulations (Sweden’s Building Regulations)
BR18	Bygningsreglementet 2018 (Denmark’s building regulation 2018)
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
CIE	Commission Internationale de l'Éclairage (International Commission on Illumination)
CS	Climate Studio
DF	Daylight Factor (%)
EU	European Union
FAR	Floor Area Ratio
GFR	Glass-to-Floor Ratio
H/W	Height-to-width ratio
IC	Internal Climate
IES	Integrated Environmental Solutions
LEED	Leadership in Energy and Environmental Design
nZEB	Net Zero Energy Building
OSR	Open Space Ratio
sDA	Spatial Daylight Autonomy (%)
sDG	Spatial Disturbing Glare (%)
SVF	Sky View Factor
SVL	Solvärmelast (Solar Heat Load)
TEK17	Byggteknisk forskrift (Norway’s national building regulation)
UDI	Useful Daylight Illuminance (%)
$\mathbf{UDI_a}$	UDI autonomous (%)
VSC	Vertical Sky Component (%)
VLR	Visible Light Reflectance (%)
WWR	Window to Wall Ratio

1 Introduction

The global population is currently experiencing a rapid transition toward urban living. Over the past century, the share of people living in urban areas has grown significantly - from approximately 10% of the world population in early 20th century to over 50% by the end of it - and this trend continues. The primary drivers of this rural-to-urban migration are the human desire for better living conditions, improved quality of life, and greater personal safety and security. These factors have collectively contributed to rapid and large-scale urbanisation across the world (Grimm et al., 2008).

The simultaneous growth of population and the unplanned expansion of the built environment in major urban areas have intensified competition for natural and infrastructural resources. One of the key consequences of this competition is the unregulated densification of cities. Driven largely by financial pressures, real estate development has often proceeded without adequate consideration of human well-being and sustainable growth. As a result, densely populated urban areas frequently fail to provide their inhabitants with access to essential natural resources, including clean air, potable water, open spaces, and adequate natural light (Seto et al., 2017). Poorly planned high-density cities are often associated with increased noise levels, degraded air quality, stronger urban heat islands, reduced natural ventilation, loss of green space, and negative effects on both physical and mental health. Importantly, many of these problems stem from how densification is carried out, rather than from density itself (Loibl et al., 2021; Palusci et al., 2022). Among the essential natural resources affected by urban densification, access to sunlight emerges as a particularly critical concern - especially in regions where geographic and climatic conditions already limit its availability.

Daylighting plays an important role in human health, visual comfort and building energy performance. The human physiology operates on a 24-hour circadian rhythm that depends on natural light, not just for vison but also for regulating sleep cycles, hormonal balance, metabolism, immune response, and cognitive performance. Exposure to natural light has significant implications for both physical and psychological wellbeing. Controlled studies have demonstrated that an increase in daylight exposure improves circadian alignment, sleep quality, and mental health outcomes (Nagare et al., 2021). Similarly, research on residential environments shows that daylight and view through windows significantly affect psychological wellbeing (Veitch et al., 2012).

In Nordic countries, daylight becomes particularly critical due to high latitude, low solar altitude and prolonged winter darkness. Cities like Luleå, Stockholm and Lund experience a shallow solar angle during winter, resulting in longer shadows and reduced facade solar exposure. In addition, meteorological conditions such as persistent overcast skies and frequent fog further reduce the availability of natural light, particularly during the colder months of the year (Dubois et al., 2025). This limited access to daylight makes it a scarce and valuable resource, which must be carefully considered in the planning and design of the urban built environment. Under such conditions, the urban form becomes the primary factor that determines how much of direct sunlight and diffuse daylight the buildings receive. The arrangement of streets, the orientation and heights of buildings, and the width of street canyons all greatly influence how sunlight penetrates the urban landscape. Manipulating these geometric relationships influences how direct sunlight and diffuse daylight reach the streets, facades, courtyards, and interior spaces.

As cities continue to densify, urban forms that restrict daylight in buildings become increasingly common (Rostami et al., 2024). Among the geometric parameters that urban planners must determine, street orientation plays a crucial role. The direction in which the street and buildings are aligned to the sun path directly affects solar exposure throughout the day and across the seasons. Certain orientations may allow more balanced sunlight distribution while others may result in significant shading and reduced daylight availability. Numerous studies have explored the impact of increasing urban density on daylight access, examining the subject through varied analytical frameworks.

These studies (Compagnon, 2004; Sattrup and Strømann-Andersen, 2013; Strømann-Andersen and Sattrup, 2011) have collectively considered a range of contributing factors, including street canyon geometry, height-to-width ratios, building regulations, urban planning policies, and the spatial arrangement of the built environment. Additional research (Czachura, Gentile, et al., 2022; Formolli et al., 2023; Sokol & Martyniuk-Peczek, 2016) has investigated how key urban design features, such as the provision of open spaces, internal courtyards, and green infrastructure, affect the overall solar performance of buildings and their surrounding areas.

Existing literature (Bournas and Dubois, 2019; Rohde et al., 2024; Sattrup and Strømann-Andersen, 2013; Volf et al., 2024) also includes case studies of major cities across the world, highlighting key shortcomings in daylight performance within dense urban environments. Despite growing research in the field of daylighting and solar access, there remains a lack of studies that effectively bridge the relationship between densifying cities and sustainable development, particularly regarding the optimised use of natural light for exterior and interior illumination. Furthermore, regulatory aspects such as right-to-light provisions are insufficiently addressed in most of the research literature reviewed. One study within the same domain employs an integrated analysis of outdoor spaces, building envelopes, and indoor environments to support early-stage planning decisions in the Norwegian context (Formolli et al., 2022). However, despite being grounded in the Nordic setting, key parameters such as street orientation and height-to-street ratio receive limited attention in that study.

Research by Czachura, (2023) identifies the major factors influencing solar access and underlines its significance for urban planning, particularly in dense cities at higher latitudes. The author positions solar access as a prerequisite for both energy performance of buildings and public well-being. It further highlights how early-stage planning decisions can have a considerable impact on solar access outcomes at later stages, demonstrated through simulation-based performance analysis. While street orientation is acknowledged and its qualitative effects on facade metrics are discussed, the study does not involve a systematic and dedicated analysis of optimal street grid orientations across different latitudes. Additionally, the variation in parameters such as building height and street width remains limited. Finally, despite the range of performance indicators discussed, the study does not define minimum acceptable thresholds to assess the performance of solar access.

Consequently, despite covering a wide range of geographic locations, local standards, and individual comfort levels, existing literature provides limited information on the combined effect of street orientation and solar access in high-latitude regions, particularly within the Nordic context. This gap in existing knowledge forms the primary basis for the present study. Understanding how street orientation influences sunlight access, is essential for developing urban planning strategies that support sustainable and healthy residential development, particularly in the Nordic region.

1.1 Aim and objectives

The overall aim of this thesis is to contribute to better urban planning and housing design in Sweden by improving the understanding of how street orientation influences access to diffused daylight and direct sunlight in residential buildings. By clarifying the relationship between urban form and indoor daylight conditions, the thesis seeks to support long-term improvements in the quality, sustainability, and liveability of future urban environments.

To achieve this broader aim, the thesis is guided by the following research questions:

RQ.1. How does street orientation influence sunlight access in residential buildings located in Nordic climatic conditions characterized by high latitude, low solar angles, and strong seasonal daylight variation?

RQ.2. How does street orientation affect daylight availability in residential blocks with varying building heights and street-canyon widths?

RQ.3. How does sunlight distribution vary across different building floors when accounting for shading effects and facade exposure from adjacent buildings?
RQ.4. How do the effects of street orientation differ across the three Nordic cities of Lund, Stockholm, and Luleå, given their distinct latitudes?
RQ.5. What design recommendations can be developed to support early-stage urban planning decisions for residential areas in Nordic climatic conditions?

1.2 Scope and limitations

This study focuses on simulation-based assessments of daylight performance, considering both direct sunlight and diffuse daylight access in Nordic residential courtyard buildings. The scope is deliberately defined and limited. Post-occupancy evaluations, social surveys, and economic considerations are excluded. Although visual comfort aspects, such as glare, are recognized as important in practice, they are not included within the primary scope in order to maintain a clear and manageable research focus. These boundaries reflect a deliberate emphasis on depth of one topic rather than breadth over a vast area, with the aim of producing findings that are both methodologically rigorous and practically relevant for early-stage residential design in Nordic urban contexts.

1.3 Background

1.3.1 Historic importance of daylighting in urban planning and street orientation

The relationship between urban form and sunlight access can be seen throughout the history of urban planning. Ancient civilizations incorporated astronomical and solar principles into the design and orientation of settlements, showing a deep understanding on the benefits of sunlight in built environment. For example, with respect to building architecture, the Temple of Amun at Karnak was deliberately oriented to allow sunlight to penetrate along the central axis of the hypostyle hall, with the winter solstice sunrise casting light through the monumental gateway. Greek temples were similarly oriented to face east, allowing the morning sun to illuminate their gods' statues at sunrise. However, in both civilizations, sunlight was primarily used to emphasize exterior form rather than to illuminate interiors. Still, the need for solar access was one of several factors that motivated the development of the orthogonal town plan in ancient Greece (Dubois et al., 2025).

Roman towns are among the most documented examples of solar oriented urban planning. Roman towns followed a grid pattern structured around two primary axes: the cardo (north-south axis) and decumanus (east-west axis). Study by Magli, (2008) demonstrated that many Roman towns in Italy were deliberately aligned with solar events, including solstices and annual sunrise directions. Although symbolic motivations were present, such alignments also improved the sunlight exposure along the streets and within urban blocks.

1.3.2 Daylight in contemporary architecture

In contemporary architectural practice, daylight is no longer considered merely as a free natural source of illumination but rather as a key driver of sustainable development. Its implications for human well-being and its role in synchronising the circadian rhythm have led to a greater integration of daylighting strategies into the built form (Mukherjee and Boubekri, 2025). Advancements in the field have facilitated the incorporation of dynamic facades, rooftop skylights, automated shading systems, and optimised atria, which have collectively contributed to improved daylight performance and reduced overall energy consumption (Garcia-Fernandez and Omar, 2023). Furthermore, the technological evolution of computer-aided design and advanced building simulation tools focused for daylight and energy performance analysis has enabled to foresee key implications for design (Dubois et al., 2025). These concepts and technological advancements are leading to a more comprehensive integration of sustainable development principles in contemporary architecture across the world.

1.3.2.1 Regulatory and advisory framework for daylight

Daylight and solar access requirements have evolved from simple geometric rules, such as window size, building form, and obstruction angles toward more advanced, climate-based performance metrics. These requirements vary considerably across individual countries, EU-level standards, and voluntary environmental certification systems. Despite these differences, the existing regulatory and advisory framework can be broadly classified into four categories, each serving a distinct role and directive: building laws and regulations, standards, guidelines, and environmental certification systems.

1.3.2.1.1 Building laws and regulations

Building laws and regulations constitute legally binding frameworks, where non-compliance can result in the blocking of construction permits or lead to legal and financial penalties. These regulations typically employ simple performance metrics such as DF, minimum solar hours, and WWR, with clearly defined minimum acceptable thresholds. They are generally applied prior to building permit application. Examples within this category include national building regulations such as the Swedish building regulations (BBR) and Norwegian building regulations (TEK17), as well as specific urban and zoning rules governing minimum building setbacks, maximum building heights, overshadowing restrictions, and rights to sunlight (Hachem Vermette et al., 2024; Kanters et al., 2021).

1.3.2.1.2 Standards

Standards are technical norms established by independent bodies, grounded in research and academic justification. While they are frequently referenced by law, they do not constitute a legal mandate. Standards generally provide detailed descriptions and procedural guidance for measuring performance metrics - such as ASE, sDA, UDI and DF rather than serving as design guidelines (Hraška and Čurpek, 2024). Notable examples include the recent European Standard EN 17037 Daylight in Buildings, Swedish standard SS 91 42 01-Dagsljus i Boverkets byggregler (BBR), which is no longer valid, and various national performance standards adopted across different countries (De Luca and Sepúlveda, 2021).

1.3.2.1.3 Guidelines

Guidelines constitute non-binding design advice that may be used during planning and design decisions, but they carry no mandatory obligation. They are particularly useful for architects and urban planners when applying laws and standards, as well as when exploring design alternatives that balance daylight availability and solar gains (Bournas, 2020).

1.3.2.1.4 Environmental certification and rating systems

Certification and rating systems are voluntary market-based tools with no legal binding, used to evaluate buildings based on their performance metrics. They often apply stricter acceptance criteria than regulatory requirements and can contribute to increasing the environmental sustainability and financial value of properties (Bournas, 2020). While these systems are generally voluntary, governmental and regional authorities can require specific certification levels in certain contexts. In Sweden several municipalities require all new public buildings to achieve Miljöbyggnad Silver certification to comply with local environmental directives (Forsberg and de Souza, 2021; Francart et al., 2022). For example, regional governments which own and operate most hospitals, mandate this level in their building policies to meet local climate goals. At the global level, widely recognised certification schemes include LEED, BREEAM, and WELL, while in the Nordic context, Miljöbyggnad and NollCO2 are among the most established certification frameworks.

1.3.3 European context and European standard (Daylight in buildings-EN 17037)

The European Standard EN 17037:2018+A1:2021 is the main framework for assessing daylight in buildings. It treats daylight as the preferred source of illumination in occupied spaces, measured through illuminance levels across a reference plane over defined time periods. The standard addresses four key areas: daylight provision, view out, exposure to sunlight, and protection from glare. For daylight provisions, the standard requires that a target illuminance of 300 lux is achieved across at least 50% of the reference plane, located 0.85 m above the floor, for at least half of the annual daylight hours. In addition to it, exposure to sunlight is measured as the total number of hours of direct solar radiation received at a defined interior point, assessed at three levels - minimum, medium, and high on a date between 1 February and 21 March.

Although Sweden has adopted EN 17037 as a national standard (SS-EN 17037), it is not a requirement in the national building code and is used only on a voluntary basis. Its requirements have proven difficult to meet, the study by Jin et al., (2025) show that only 16% to 45% of rooms in existing Swedish residential buildings comply to EN 17037, regardless of which calculation method is applied. This also reflects both how demanding the standard is and the challenge of the Swedish northern climate. Sweden is not alone in this; almost no European country has formally adopted EN 17037 as a mandatory building code requirement (Bournas, 2020).

At the national level, Sweden's daylight requirements have long been established by the Swedish National Board of Housing, Building and Planning (Boverket) building regulations (BBR), which required a minimum point DF of 1% in rooms with regular occupancy. This threshold was introduced after the 1970s energy crisis to ensure buildings retained adequate natural light despite shrinking window areas (Rogers et al., 2025). It remained the foundation of Swedish daylight regulation until the 2025 BBR revision, which moved compliance assessment from individual rooms to the dwelling as a whole and removed the direct sunlight requirement entirely (Boverkets (2024:14) ;Boverkets (2011:6)). Note that the 1% requirement in each room occupied more than occasionally has been removed for non-residential premises but it is still a good practice to verify this DF value in real building projects.

A significant limitation of both EN 17037 and BBR is that neither addresses street width, building orientation, or urban block geometry. In Sweden, daylight compliance is checked by developers at the building permit stage, with no requirement to assess daylight when preparing detailed development plans - the documents that determine how a neighbourhood is laid out and how tall buildings can be (Kanters and Wall, 2018). This is particularly problematic in countries, where low winter solar altitudes mean that planning decisions about street direction and building height have a large and lasting effect on how much daylight buildings receive. This gap between planning decisions and daylight regulations has been identified as a key challenge and bottleneck of the building design process (Sokol and Martyniuk-Peczek, 2016). In response, researchers proposed simulation-based daylight methods as practical tools for shaping zoning regulations (Saratsis et al., 2017), with newer approaches now able to optimise daylight, energy performance, and photovoltaic potential at the same time (Liu et al., 2024), which shows that urban geometry can be meaningfully assessed and integrated into the planning process.

1.3.4 Daylight regulation in Swedish urban planning

1.3.4.1 A brief history of Swedish regulation and daylighting

The relationship between city planning and daylight access in Sweden has a history stretching back over 150 years. The first national building code of 1874 explicitly required that urban plans should satisfy what was described as the hygienic demands of light, and this was primarily achieved by regulating the distance between buildings and their maximum height relative to street width (Bülow-Hübe et al., 2022). In the building codes of 1931, 1947, and 1959, this principle was formalised as a requirement that building height should not exceed the distance between facing facades, which produced a maximum obstruction angle of 45 degrees from street level. The 1947 code went further by explicitly stating that plans should secure good daylight conditions within blocks and provide as many apartments as possible with cross ventilation and direct sunlight (Bülow-Hübe et al., 2022).

Detailed daylight requirements in prescriptive form appeared for the first time in the Swedish Building Standard (SBN) of 1975, which introduced the DF as a measurable compliance criterion. A minimum DF of

1.0% at a defined reference point was required for habitable rooms, and this threshold has remained essential in Swedish regulations ever since in BBR under section 6:322 (Bülow-Hübe et al., 2022). In that same year, we also saw the introduction of maximum permitted window areas as part of new energy conservation rules, creating a conflict between energy efficiency and daylight provision that has persisted in Swedish building practice. However, the minimum DF requirement was changed in the latest edition which came into force in 2025 (BBR 31) (Boverkets (2024:14)).

Research has documented that daylight availability in Swedish apartments was at its highest in buildings constructed between 1930 and approximately 1960, during the period when Modernist planning ideals promoted well-separated buildings oriented to admit light and air (Bournas, 2021). Since then, the combination of increasing urban density, energy-driven reductions in window area, and architectural trends towards deep floor plates and large balconies has steadily eroded daylight conditions in new residential construction (Rogers et al., 2025).

1.3.4.2 Geographic location and its implications on solar access

Sweden spans a wide latitudinal range, from approximately 55.5 degrees north for Malmö to over 67 degrees north in the far north, resulting in considerably different solar conditions across the country. At the winter solstice, solar noon altitudes are roughly eleven degrees in Lund, seven degrees in Stockholm, and barely two degrees in Luleå (Bülow-Hübe et al., 2022). These low solar altitudes cast long shadows from buildings, implying that even moderately sized structures can block sunlight from streets and courtyards for much of the day. As latitude increases, seasonal variation in day length and solar altitude becomes more extreme, making orientation effects on solar access increasingly significant (Compagnon, 2004). A street configuration that provides adequate sunlight in Lund may therefore be entirely inadequate in Luleå.

Standard EN 17037:2018 recommends evaluating solar access for a reference date between 1 February and 21 March, with a minimum of 1.5 daily sun hours at an interior reference point (Bülow-Hübe et al., 2022). The standard does not require or define how large the sunlit patch must be within a room. Instead, compliance is based solely on whether direct sunlight reaches the reference point for the specified duration. At Nordic latitudes, this is a demanding requirement, as solar altitudes remain very low during this period. Existing literature (Compagnon, 2004; Nasrollahi and Shokri, 2016) indicates that meeting this minimum threshold in north-facing, single-sided apartments within dense street canyons at high latitudes is practically unfeasible.

1.3.5 Nordic regulations and by-laws

In Nordic countries, daylight availability is a critical factor due to high latitude and limited winter solar radiation. In Sweden, the daylight requirements are addressed through the BBR, as explained earlier. These regulations require that buildings provide sufficient daylight to ensure acceptable indoor quality, while no single metric is mandated but DF assessments and climate-based simulations are commonly applied in - practice.

Research evaluating Swedish residential buildings shows that compliance to daylight standards remain inconsistent. Bournas and Dubois (2019) found that a significant proportion of existing multi-family housing did not meet recommended daylight thresholds, particularly on lower floors in dense developments.

Planning routines in Sweden show that indoor daylight is increasingly assessed during early planning stages, although outdoor solar access and street orientation remain less systematically studied or regulated (Kanters et al., 2021). Daylight research in the Nordic countries further emphasizes the importance of climate-responsive design under northern sky conditions (Dubois et al., 2025). Broader sustainability frameworks also highlight solar access as essential for smart, low-carbon urban development (Hachem Vermette et al., 2024; Manni et al., 2023).

Given the present climatic and regulatory conditions, integrating street orientation into early stages of urban planning may potentially improve daylight and sunlight access and distribution, as well as the overall building energy performance.

1.3.5.1 Swedish regulations (BBR) on daylight and sunlight access

Swedish building regulations have undergone a significant transition over the past decade, shifting from prescriptive daylight rules toward performance-based requirements. This evolution is directly relevant to the examination of how urban form and street orientation influence daylight access in Nordic residential buildings.

Under BBR 19, daylight provision was verified using the national standard SS 914201, requiring window glazing of at least 10% of the floor area - assumed to yield a daylight factor of approximately 1%. The regulations also stipulated that at least one room per dwelling should receive direct sunlight for part of the day. BBR 25 (2019-2021) represented a transitional phase, during which the industry continued to rely on the 10% glazing rule while Boverket prepared the framework for performance-based assessment, without introducing any new mandatory calculation method.

A more substantial shift occurred with BBR 31, which introduced a mandatory performance-based daylight metric, requiring verification through the median daylight factor with a minimum of 1% for rooms intended for permanent occupancy. The previous sunlight requirement was removed, though many practitioners continue to reference sunlight access as an indicator of residential quality. BBR 31 retains the requirement that at least one window must allow occupants to perceive natural variations in daylight across the day and seasons.

This transition has important implications for urban analysis, as the performance-based approach of BBR 31 places actual daylight availability at the centre of regulatory compliance, aligning Swedish practice more closely with international standards such as EN 17037.

1.3.5.2 Miljöbyggnad 4.1 and sunlight access in residential buildings

Miljöbyggnad is a national environmental certification system widely used in Sweden to evaluate residential and non-residential buildings across aspects of indoor environmental quality, energy use, and building materials. As many Swedish housing projects target Miljöbyggnad certification, it influences design decisions related to facade orientation, window configuration, and indoor climate.

A key change in the most recent version, Miljöbyggnad 4.1, is the removal of a dedicated daylight indicator. Earlier versions, such as Miljöbyggnad 3.0, required either a daylight factor calculation or compliance with window-to-floor-area rules. These requirements have been removed, and daylight performance is now assumed to be regulated through the national building code - BBR. Consequently, Miljöbyggnad 4.1 does not assess daylight availability or sunlight access as separate criteria. Daylight availability is nonetheless addressed indirectly through the requirement that windows in occupied rooms must have a light transmittance of at least 0.6 to achieve higher certification levels. If this value is not met, compliance with BBR daylight provisions must be demonstrated through a separate daylight calculation, ensuring that glazing choices do not unnecessarily reduce daylight access.

Solar exposure continues to be assessed through the solar heat load indicator - Solvärmelast (SVL) - which evaluates overheating risk based on solar radiation entering through windows. Only facades oriented between east and west via south are included, meaning street orientation and surrounding buildings directly influence the result. In summary, Miljöbyggnad 4.1 addresses solar gains and overheating risk, while daylight and sunlight access are no longer evaluated as standalone indicators, with this responsibility delegated to BBR.

2 Literature review

In Nordic cities, access to daylight and sunlight is a key issue because of low solar altitudes and dark overcast winter periods. The way streets are oriented and how buildings are arranged can strongly influence how much daylight and sunlight reaches facades, streets, open, and interior spaces. Several studies have explored this relationship using simulation methods, urban analysis, and historical perspectives.

2.1 Historic and foundational studies

A historical perspective is presented by Magli (2008), who studied the orientation of Roman towns. His research shows that many Roman cities were aligned with cardinal directions or with the position of the sun during solstices. In some cases, towns were oriented to capture low-angle sunlight, especially during winter. This suggests that the relationship between urban form and solar access has been considered for a long time. These ideas are still relevant today, especially in northern regions where sunlight is limited (Magli, 2008).

Later, Antón et al., (2016) showed through analysis that the foundations of Roman towns follow deliberate non-randomized street grid orientations. This suggests that the Romans intentionally included solar and celestial alignment principles when establishing urban areas. Using a large database of documented orientations of settlements, they performed statistical tests to confirm that town orientations cluster around solar azimuths, specifically at sunrise and sunset positions on important dates, rather than following a random distribution. The authors argue that this orientation was a foundational and intentional aspect of Roman urban planning. However, the study carries significant limitations. A non-random orientation distribution does not clearly prove or confirm the deliberate solar intent, since clustering could also equally be a result from topography constraints, prevailing wind directions or pre-existing boundary lines. More importantly for this thesis, archaeological and astronomical methods do not apply to modern, scientific based approaches. It lacks metrics like performance data and no qualitative or quantitative relevance to contemporary street planning strategies used in the Nordic region. Therefore, the paper's value is primarily conceptual, but it has established that there is a link between street orientation and solar access, and this strategy has been used since ancient times.

2.2 Contemporary studies

One important study by Compagnon (2004) develops a method to calculate solar irradiation and daylight on building surfaces in dense urban areas. The study shows that even when density is kept constant, different urban layouts can lead to large differences in solar access. This means that geometry, including street orientation and building arrangement, plays a major role in how much sunlight is available. Compagnon's method is useful at the early design stage because it allows planners to compare different urban forms and understand their impact on solar potential and shading.

A study by Boeing, (2019) examined street network orientation in one hundred cities around the world. This paper introduces the idea of orientation entropy, which measures how street directions are distributed within a city. If streets follow many different directions, the entropy is high. If most streets follow a similar direction, the entropy is low. This helps to describe how ordered or irregular a street network is in a simple and measurable way. To make this concept easier to use, Boeing also develops an orientation order indicator, shown as φ. This value ranges from 0 to 1. A value close to 1 means that the city has a strong and consistent grid, while a value closer to 0 indicates a more irregular grid. This allows different cities to be compared using a single value, even if their forms are very different (Boeing, 2019).

Boeing's study shows that many cities tend to follow certain dominant street orientations, parallel to cardinal directions. About half of the cities analysed show this tendency. This is important because these directions are closely related to how sunlight moves during the day. Street orientation can therefore influence how sunlight enters urban spaces and reaches building facades. Boeing also finds that street orientation is linked with other properties of urban form. Cities with a strong orientation order often have more connected street networks, with more intersections and more direct routes. In contrast, cities with irregular orientations tend to have more complex layouts and less direct movement patterns. These differences can affect how light and shadow occur in urban areas. The study also highlights differences between regions. Cities in North America often have more regular grid patterns, while many European cities have more irregular street layouts. This is relevant for Nordic cities such as Lund, Stockholm, and Luleå, which often have a mix of historic street patterns and newer planned areas. Although this study does not directly measure sunlight or daylight, it provides a useful way to understand and compare street orientation. Since solar access depends on the direction of streets and buildings, these metrics can help to explain how different urban forms may influence sunlight conditions. This makes the study relevant for analysing daylight and solar access in Nordic cities.

More recently, Hachem Vermette et al., (2024) highlighted that urban planning regulations are the primary administrative tools for shaping the built environment, directly impacting building placement, height, and street relations. They argue that urban densification being a key global trend, existing building codes and zoning laws often lack the specificity needed to protect daylight availability and facilitate large-scale solar technology deployment. Their study compares planning regulations and building bylaws from different countries focusing on daylight requirements and solar energy performance. Daylight and Visual Comfort requirements found in that study are listed below:

- Italy: Employs strict quantitative metrics, requiring a minimum DF of ≥ 2% in primary rooms (i.e., room in which the occupants are permanently present) for residential buildings and ≥ 3% in classrooms and labs for schools and hospitals. It also mandates that window surface area must be at least 1/8 of the useable floor area, for rooms smaller than 100 sq.m in floor area.
- Norway: Distinguishes between "light" and "view," requiring an average DF of 2% for the most critical room or compliance through specific glass-to-floor area equations. It also explicitly requires that rooms for permanent stay have a "satisfactory view".
- Canada (Local Level): While no national solar access law exists, specific municipal plans like Toronto's Official Plan prioritize sunlight and sky views by mandating adequate separation distances between building walls.
- Sweden: Municipalities like Malmö utilize the Vertical Sky Component (VSC) and obstruction angle analysis during early planning phases to ensure daylight requirements will be met.

When discussing at building level, a study by Rohde et al., (2024), indicates that urban densification driven by sustainability goals often leads to taller buildings placed in closer proximity, which in turn makes it increasingly challenging to satisfy national daylight requirements, specifically for dwellings located at the lower levels. While Norway and Sweden permit basement dwellings if they meet established daylight and view standards, Denmark and Iceland enforce the strictest restrictions. In Iceland, the ban was introduced recently to prevent the creation of dwellings with "depressing visual conditions," a problem linked to historically insufficient daylight provisions in their regulations. Two primary methods from Danish Building Regulations (BR18) described in the study can be used to evaluate daylighting:

- The 10% Rule: This traditional method mandates that the relevant glass area must correspond to at least 10% of the floor area, adjusted by various correction factors for shading.
- The 300 Lux Method: Based on DS/EN 17037 standards, this method requires that illuminance from daylight reaches 300 lux or more for at least half of the floor area during at least half of the daylight hours. Additionally, the Compensation Method, which allows for slightly lower daylight levels in certain rooms (like bedrooms) if the living room provides daylight levels above the minimum specified threshold.

In the same study, two examples employing CS software to simulate daylight autonomy in distinct contexts showed that:

- In a low-rise suburban context, a simulated basement apartment in a two-story multifamily house, daylight requirements were achievable. At elevations of -850 mm and -1450 mm relative to the ground, the rooms achieved the 300-lux threshold for more than 50% of the calculation surface. However, the kitchen/living area in this specific layout remained just below the 50% threshold.
- While in a high-rise urban context, the simulations for a basement apartment in a five-story residential block revealed significant challenges. Compliance with the 300-lux method was only achieved when the distance to the neighbouring five-story building was 40 meters or greater. For the kitchen specifically, compliance required a distance of at least 60 meters due to its northeast orientation and lower elevation relative to the street side.

In Sweden, a study by Bournas (2020), highlights several key factors that strongly influence whether a room satisfies daylight requirements.

- Vertical Sky Component (VSC) and Glass-to-Floor Ratio (GFR): These emerged as the most reliable predictors of daylight performance, whereas commonly used indicators, such as window-to-wall ratio (WWR) and total glass area, proved to be weak or inconsistent predictors of indoor daylight levels.
- Building Typology: High-rise towers achieved the highest compliance across all criteria. In contrast, developments featuring exterior circulation, large courtyard blocks, or postmodern layouts performed poorly, often because balconies and dense surroundings obstruct the sky hemisphere.
- Urban Density: Daylight compliance declines sharply as urban density increases. Among the evaluated metrics. He also found that the metric UDI best captured the influence of surrounding obstructions on indoor daylight availability.

Also in Sweden, Czachura, Kanters, et al., (2022) provided a critical overview of how metrics are used to evaluate solar and daylight access during the early stages of urban design. Sustainable urban development requires integrating solar strategies early to achieve nearly zero-energy buildings (nZEB). However, solar assessments are often neglected in practice due to a lack of established routines, limited expertise among planners, and high computational loads. These authors emphasize that while Internal Climatic (IC) metrics (like energy use or visual comfort) are highly accurate, they are often unsuitable for early urban planning because they require detailed information about interior layouts and material properties that are unknown at that stage. The study categorizes metrics into a taxonomy based on data complexity, with Sunlight and Daylight being assessed through different classes:

- Latitudinal (L) metrics (Sunlight): These are "sun-only" metrics that account for the solar position based on latitude and building orientation but ignore climate data like cloud cover.
- Sunlight Exposure (facade): This metric quantifies the duration of cloudless direct sunlight received by a facade. It is used in the SS EN 17037 standard, which recommends that at least one habitable room in a dwelling receives a minimum of 1.5 hours of direct sunlight on a date between February and March.
- Two-hour area (ground): Recommended by the BRE guide, this metric suggests that at least half of a garden or amenity area should receive two hours of sunlight on the spring equinox (Littlefair, 2001) .

Similarly, the layout and orientation of streets and buildings significantly influence solar availability.

- Street Orientation: Building orientation is described as imperative for passive solar design. Interestingly, the authors note that while orientation changes the Area of Permanent Shadow (APS) on a courtyard ground, it may not affect the cumulative solar radiation received by the courtyard’s facades.
- H/W Ratio (Height-to-Width): This metric is used to study urban canyons (streets). There is a noted conflict in objectives: microclimate studies often advocate for high H/W ratios (narrower streets) to

provide shade, whereas solar potential studies support lower H/W ratios to increase solar access on facades.

- Open Space Ratio (OSR): A three-dimensional metric that expresses the ratio of site open space to gross floor area, helping planners understand how much outdoor space is available per unit of indoor floor area.

Research (Czachura, 2023.; Czachura et al., 2024; Czachura, Gentile, et al., 2022; Czachura, Kanters, et al., 2022) by the same author focuses more directly on solar access and daylight in Northern European cities. Her work is especially useful because it provides clear metrics and simulation methods that can be applied to Nordic conditions. In her study (Czachura, Gentile, et al., 2022), it is shown that as urban density increases, buildings block each other and reduce access to sunlight. This effect becomes more critical at higher latitudes, where solar altitudes are lower. To study this, she uses several indicators. These include VSC, which measures daylight on building facades, and SVF, which describes how much of the sky is visible from streets or open spaces. She also uses Annual Sunlight Hours on facades and sunlight hours on the ground for specific days. These metrics help to evaluate both indoor and outdoor light conditions. Her research also shows that these indicators are strongly related to urban density and form. For example, deeper street canyons and taller buildings reduce both daylight and direct sunlight. By testing different building types and rotating them in simulations, she demonstrates how orientation affects solar access. The study uses tools such as Ladybug and Honeybee with climate data for cities like Stockholm, which makes the results relevant for Nordic environments (Czachura, Gentile, et al., 2022). Overall, Czachura's research provides a strong methodological base for studying sunlight in urban areas. It offers clear metrics, and links to tested simulation approaches, all of which are useful for analysing impacts of street orientation in this thesis.

Together, these studies show that urban form and street orientation have a strong influence on solar access. They also provide methods and concepts that can be used to compare different cities and understand how their layouts affect daylight and energy potential.

2.3 Research gap

Despite the increased awareness of the importance of daylight and solar access in urban planning, there remains limited research focusing specifically on the influence of street orientation on daylighting, sunlight access and energy performance in Nordic built environment. Many studies have examined the relationship between urban density and daylight availability. However, relatively few studies have evaluated how street orientation influences solar parameters at the habitable spaces across different locations in Nordic climates. This thesis addresses this gap by using parametric urban modelling and climate-based simulations to evaluate how street orientation affects sunlight access and daylight availability in residential buildings in three Nordic cities: Lund, Stockholm and Luleå.

3 Methodology

This study employed a mixed-method approach to investigate how street orientation, street width, and building height affected sunlight access and daylighting performance in Nordic residential contexts. The approach combined quantitative simulation-based analysis with a qualitative review of the literature, standards, and regulations. These two components were developed in parallel, with the literature informing the selection of variables, performance indicators, and thresholds used in the simulations. The simulation results were then used to interpret and evaluate the ideas discussed in previous research.

The research followed a structured and sequential process, as illustrated in Figure 1. The study began with the formulation of the research question, followed by information gathering and a systematic literature review. Based on the findings of the literature review, the study variables were identified and categorised as dependent and independent variables.

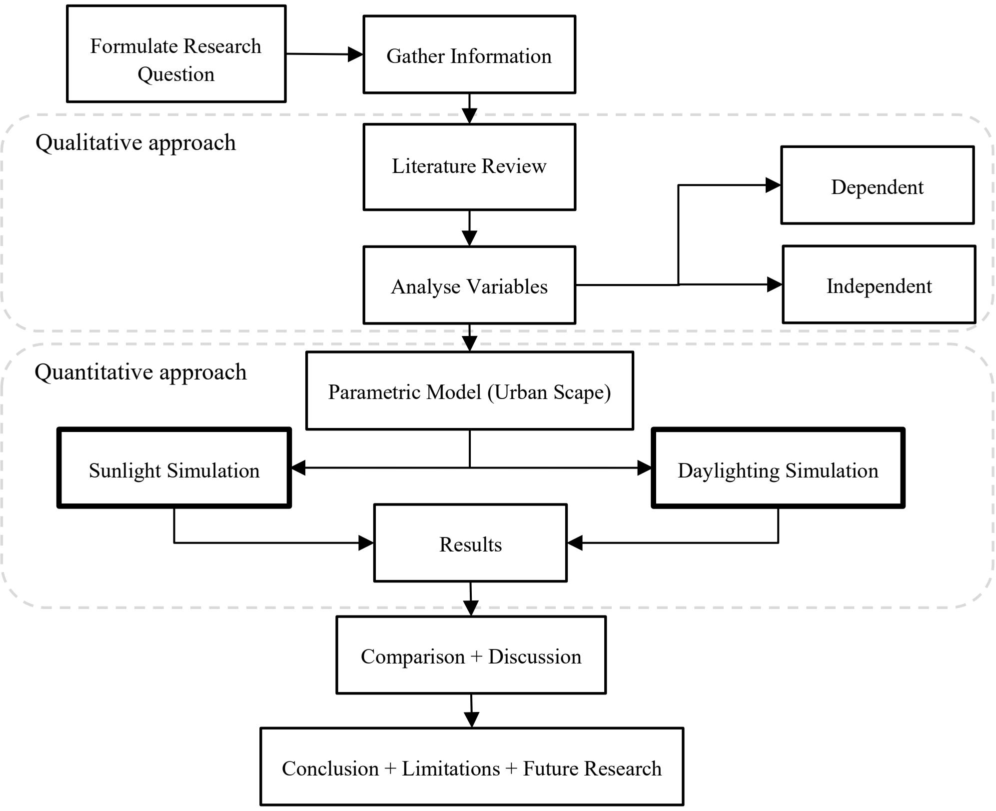


Figure 1: Work-Flow Diagram.

3.1 Qualitative approach

The qualitative part of the study is based on a review of academic literature and regulatory frameworks related to daylight and solar access. Relevant studies were collected from databases such as ScienceDirect, Web of Science, and Finn, using keywords including daylight, urban canyon, street orientation, solar access, and Nordic climate. In addition to academic papers, key standards and regulations were reviewed, including EN 17037 for daylight in buildings, the Swedish building regulations published by Boverket, and the Miljöbyggnad certification system developed by the Sweden Green Building Council. Previous work by Boeing (2019), Sattrup and Strømann-Andersen, (2013), Bournas (2020, 2021), Bournas and Dubois, (2019) and Czachura (2023) served as the main body of literature used to understand how urban form, orientation, and density influenced daylight and sunlight access in cities, particularly under high-latitude conditions. This review helped define the parameters used in the simulations and provided a basis for evaluating the results.

3.2 Quantitative approach

3.2.1 Study variables

For the quantitative part of the study, a series of computer-based simulations was carried out using a set of independent and dependent variables. The independent variables described the physical characteristics of the urban environment, including building height, street width, and street orientation. The dependent variables consisted of the performance metrics used to evaluate each case, measuring sunlight access through Direct Solar Hours (h) and ASE (%), and diffuse daylight access through sDA (%), UDI$_a$ (%), and Average Illuminance (lux), as illustrated in Figure 2.

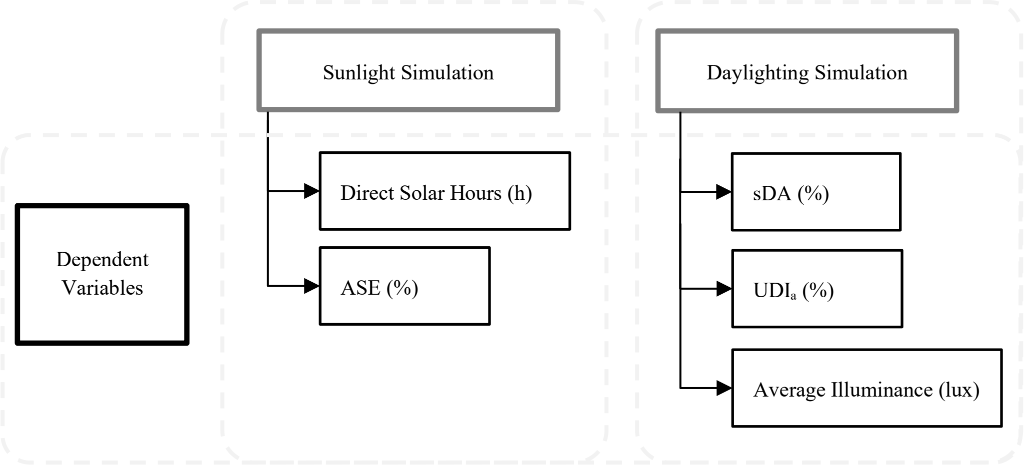


Figure 2: Dependent variables with respect to sunlight access and daylighting simulation.

In the parametric simulation model, the independent variables were systematically varied across a defined range of values, as presented in Table 1. Different combinations of these variables generated multiple urban scenarios encompassing a complete set of orientation angles, together with high-density urban configurations, which were subsequently analysed through sunlight and daylight simulations. To capture the effect of geographical variation, the analysis was conducted for three Swedish cities located at different latitudes: Luleå (65.6°N) in the north, Stockholm (59.3°N) in the centre, and Lund (55.7°N) in the south.

Table 1: Independent Variables.

Independent Variable	**Range**
Street orientation (°)	0, 30, 60, 90
Street width (m)	7.5, 10, 15, 20
Building height (No. of floors)	3, 6, 9, 12
Location and Latitude (°N)	Lund (55.7), Stockholm (59.3), Luleå (65.6)

The selection of performance metrics as dependent variables was guided by standards such as EN 17037 and IES LM-83. The sunlight access simulation output included:

- Direct Solar Hours, measured as the total number of hours per year during which direct sunlight was received across all facade surfaces and the roof; and
- ASE, calculated as the percentage of regularly occupied floor area receiving more than 1000 lux of direct sunlight for more than 250 occupied hours per year.

Analysis of these metrics enabled an assessment of the penetration and distribution of direct sunlight at both the facade level and within interior building spaces. While the diffuse daylight access simulation outputs included:

- sDA, calculated as the percentage of regularly occupied floor area meeting a minimum daylight illuminance of 300 lux for at least 50% of the annual operating hours;
- UDI$_{a,}$ calculated as the percentage of occupied hours during which a point on the work plane received daylight illuminance within the range of 100 to 3000 lux for at least 50% of the time per year; and
- Average Illuminance, measured as the annual average illuminance across the regularly occupied floor area over all occupied hours (IES-Lighting Analysis).

Through these metrics, the penetration of diffuse daylight and the corresponding dependence on artificial lighting were evaluated. Collectively, the five metrics provided a comprehensive understanding of how the independent variables influence solar access within a densifying urban context.

The total number of unique simulation scenarios across all three cities amounted to 192 for each simulation category - direct solar access and diffuse daylighting. The direct solar hours simulation produced gross total values for each scenario. In contrast, the ASE, sDA, UDI$_a$, and Average Illuminance simulations generated individual floor-level data for each scenario. All results were automatically exported to Microsoft Excel for post-processing and comparative analysis. Patterns, and trends were identified and examined in relation to the study variables. The relationship between dependent and independent variables, the overall simulation workflow, and the total number of simulations conducted are illustrated in Table 2 and Table 3.

Table 2: Relation between Independent and Dependent Variables.

		Type	**Independent**			
		Category	**Urban Planning**			
Type	**Category**	**Variables**	**Latitude** (° N)	**Street Orientation Angle** (°)	**Building Height** (No. of floor)	**Building Width** (m)
Dependent	**Diffuse Daylight Access**	**sDA** $_{\mathbf{300\ lux\ /\ 50\%}}$ (%)	X	X	X	X
		UDI$_a$ (%)	X	X	X	X
		Average Illuminance (lx)	X	X	X	X
	Sunlight Access	**Direct Solar Hours** (h)	X	X	X	X
		ASE (%)	X	X	X	X

Table 3: Total number of simulations with respect to study variables.

	Cities (Latitude)		**Building height** (No. of floors)		**Street width** (m)		**Street orientation** (°)		**Dependent Variable**				
									sDA (%)	**UDIa** (%)	**Illuminance** (lx)	**Direct Sun Hours** (h)	**ASE** (%)
Independent Variable	Lund (55.7°N)		3		7.5		0°		✓	✓	✓	✓	✓
	Stockholm (59.3°N)	X	6	X	10	X	30°	=	✓	✓	✓	✓	✓
	Luleå (65.6°N)		9		15		60°		✓	✓	✓	✓	✓
			12		20		90°		✓	✓	✓	✓	✓

No. of simulations	**x 3**	**x 4**	**x 4**	**x 4**	**Total = 192**	**+ 192**

3.2.2 Typology

A conventional rectangular courtyard-type building form was selected for this study. This typology is common in Swedish urban contexts and has been associated with high spatial density and strong solar gain performance (Sattrup and Strømann-Andersen, 2013). The base model was generated using CADMapper (2013-2024), a web-based tool that provides three-dimensional site context data, including buildings and roads, based on OpenStreetMaps (OpenStreetMap - Overview, 2020). An existing urban block in Gothenburg was selected as the reference case, as illustrated in Figure 3. The selected block was then adapted to define a standardised building footprint of 48 meters in length and 52 meters in width for use across all simulation cases. The selection of this building block size was also informed by the recommendation of Zhu et al., (2023), who suggested an aspect ratio of approximately 1:1 for courtyard buildings in cold and temperate climates, as this ratio helps to balance winter solar access and summer self-shading.

Figure 3: A typical neighbourhood of Goteborg city, Sweden (Source: Google Earth; Location: Björcksgatan 34, 416 74 Göteborg).

The floor plan had a depth of 12 meters, measured from the outer facade to the courtyard edge, and accommodated apartments on both sides of a central corridor. This consisted of a five-meter street-facing room, a two-meter zone for the structural core and circulation, and a five-meter courtyard-facing room, as illustrated in Figure 4. The five-meter room depth followed the rule-of-thumb of 1.5 to 2.5 times the window lintel height (Reinhart, 2005). Assuming a lintel height of 2.1 meters, this resulted in an effective daylit depth of approximately 5.25 meters, rounded to five meters for the purposes of this study.

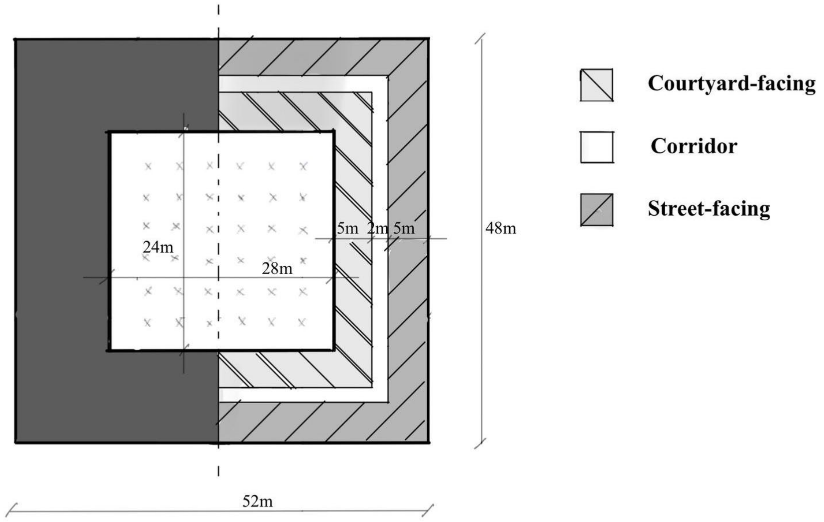


Figure 4: Illustrated zonal plan of the Modelled block.

The parametric variations in building height are kept within a maximum FAR of 5.0. This was guided by the upper recommended threshold of 5.6 reported for courtyard-type buildings (Brown and DeKay, 2014). However, it should be noted that the nine-storey and the 12-storey scenarios exceeded this recommended threshold, as presented in Table 4. As no precise upper FAR limit was defined in the Swedish building regulations (BBR, 2018; (2024:14) (2011:6), 2024), these taller cases were retained in the study to capture the full range of high-density urban conditions.

Table 4: Building height range with their respective FAR.

Building Height (No. of Floors)	**Floor Area Ratio (FAR)**
3-Floor	2.19
6-Floor	4.38
9-Floor	6.57
12-Floor	8.76

To analyse sunlight access, the outer envelope of the building was considered in each case, which provided an understanding of the extent of direct annual solar influence on the building. Subsequently, for the analysis of diffuse daylighting of interior spaces, only street-facing rooms with a depth of five metres were considered. This approach was adopted to specifically examine the influence of street orientation on daylighting conditions.

3.2.3 Context

A typical Swedish neighbourhood was modelled using a consistent building geometry within a radius of 250 meters, as illustrated in Figure 5. This extent was selected based on the study by Bournas (2021), which stated that a radius of 250 meters corresponded to an approximate simulation area of 500 × 500 meters, thereby ensuring that most of the visible surrounding context was taken into account when examining urban form and its influence on solar availability.

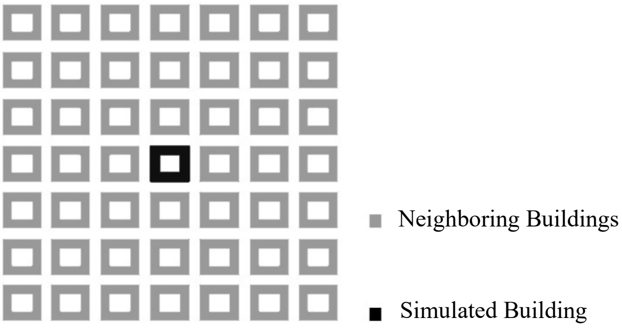


Figure 5: Simulated urban context of size 500m X 500m.

Street width and street orientation were used as a key variable in the study to understand their effect on sunlight access. Four different street widths, as illustrated in Figure 6, based on the numbers of vehicular lanes were tested: 7.5 meters (single-lane), ten meters (double-lane), 15 meters (triple-lane), and 20 meters (two double-lane). In addition, four orientation angle rotations were tested - 0°, 30°, 60°, and 90°, measured with respect to a central axis. The tested orientations are illustrated in Figure 7. Together, these variations represented a set of 16 common urban street conditions in Swedish residential areas and allowed for a comparison of how canyon width and orientation influenced solar penetration and shading patterns.

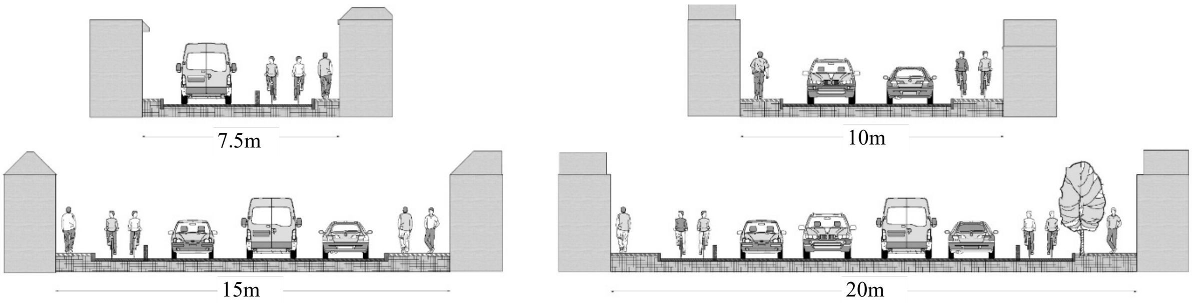


Figure 6: Street width scenarios with respect to vehicular lanes.

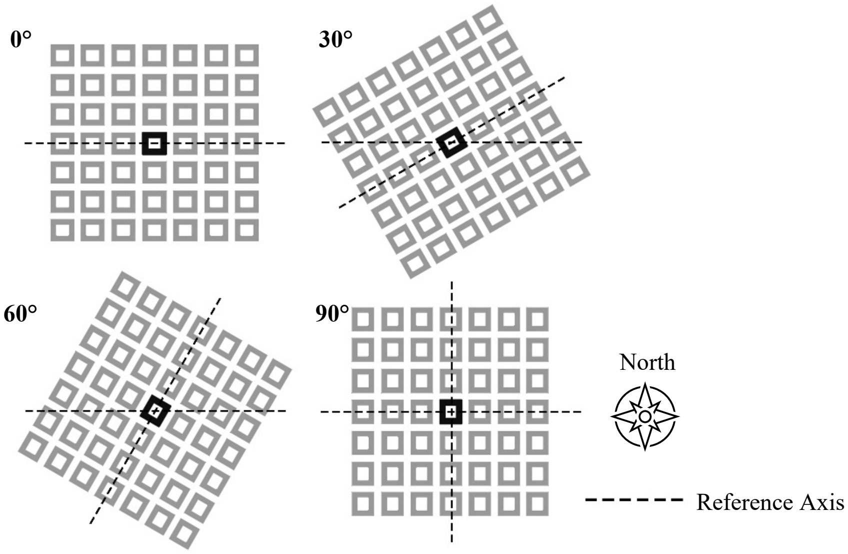


Figure 7: Street orientation scenarios with respect to central axis.

3.2.4 Software used

All three-dimensional modelling was carried out using Rhinoceros 8 and 8.5 under an educational licence. Rhinoceros is a computer-aided design (CAD) software used for three-dimensional modelling(Robert McNeel and Associates, n.d.). All parametric urban compositions and daylight simulations were developed and executed within Grasshopper, the visual scripting environment embedded in Rhinoceros. The open-source Grasshopper plugins CS, Honeybee, and Ladybug were used to run the simulation workflows. These plugins provide an interface to industry-standard programmes, such as Radiance and EnergyPlus, which serve as the core simulation engines for analysing daylighting in the built environment.

Radiance operates on a backward ray-tracing method to handle transmittance and reflectance in complex geometry, and is widely used for analysing DF, illuminance, luminance, and glare (Reinhart and Andersen, 2006). EnergyPlus is used for performance-based design and analysis, performing lighting calculations via the split-flux and radiosity method, commonly applied for calculating UDI. Additionally, EnergyPlus also provides a wide library of materials with varied properties and construction type, like glazing assembly, surface finishes, etc,(Queiroz et al., 2020). The selection of these tools was based on their established use in professional building engineering practice, as well as their relevance to the academic training undertaken during this programme.

3.2.5 Three-dimensional urban model

3.2.5.1 Base geometry model

The simulation model was developed using a single-floor courtyard block as the fundamental base unit, which was subsequently replicated parametrically through Grasshopper scripting, rather than by modelling individual rooms, floors, and building blocks.

The base model components were organised into distinct layers within Rhinoceros to facilitate the identification and assignment of material properties, construction assemblies, and sensor grid positions. Each layer represented a specific building surface geometry, including road, facade, ceiling, wall, floor, grid, windows, and surrounding context. Windows were distributed regularly along the facades of each floor to achieve an approximate window-to-wall ratio (WWR) of 0.3. The base model and layer configuration are presented in Figure 8 and Figure 9.

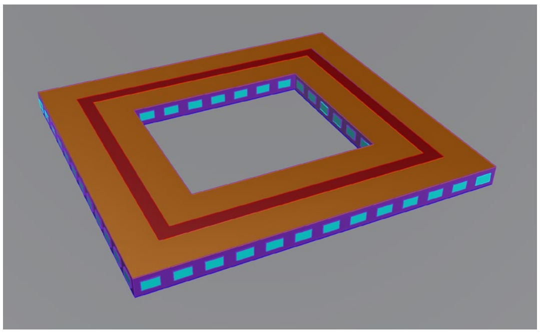
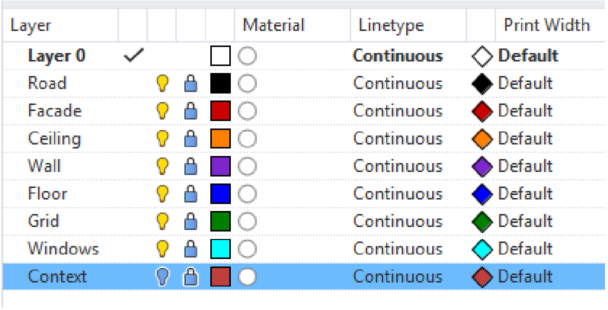


Figure 8: Base Model in Rhinoceros.



Layer					Material	Linetype	Print Width
Layer 0	✓			□	○	**Continuous**	◇ **Default**
Road		💡	🔒	■	○	Continuous	◆ Default
Facade		💡	🔒	🟥	○	Continuous	◆ Default
Ceiling		💡	🔒	🟧	○	Continuous	◆ Default
Wall		💡	🔒	🟪	○	Continuous	◆ Default
Floor		💡	🔒	🟦	○	Continuous	◆ Default
Grid		💡	🔒	🟩	○	Continuous	◆ Default
Windows		💡	🔒	🟦	○	Continuous	◇ Default
Context		💡	🔒	🟥	○	Continuous	◆ Default

Figure 9: Layer configuration in Rhinoceros.

3.2.5.2 Parametric geometry model

The single-floor courtyard block geometry was imported into Grasshopper as a base reference and was subsequently replicated and stacked using parametric scripts to generate a multi-storey building and its surrounding urban context, as illustrated in Figure 10 and Figure 11. The building block dimensions and plot size were held constant; while building height, road width, orientation angle, and geographic location were varied across the simulation scenarios.

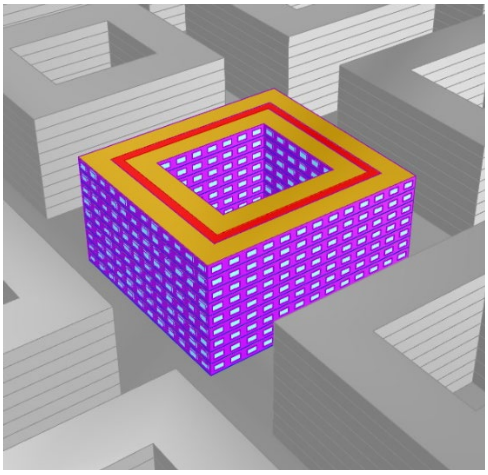


Figure 10: Parametric geometry at building level

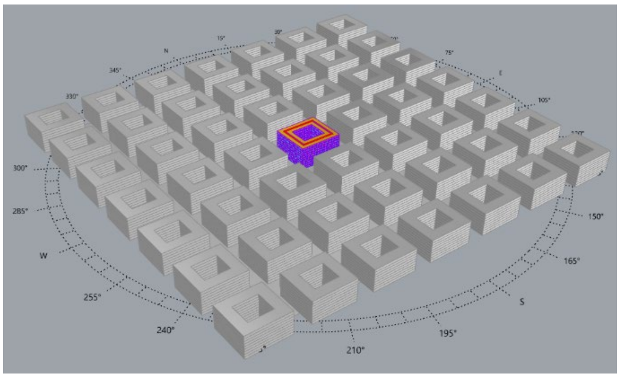


Figure 11: Parametric geometry at the context level

The analysis was conducted using a parametric workflow consisting of three main steps. First, simulation data were generated for sensors placed on the centrally located building block. Second, the TT-Toolbox plugin was used to export the results to spreadsheets for each scenario. Third, the Colibri 2.0 plugin automated the entire iterative process by systematically cycling through all combinations of independent variables without manual intervention.

3.2.6 Simulation

3.2.6.1 Simulation set-up

Annual climate-based daylight simulations were conducted in Grasshopper using CS and Ladybug, with weather files in EPW format for each of the three study cities (source: Climate.Onebuilding.Org, n.d.), as reference in Table 5.

Table 5: Swedish Cities with their respective EPW file.

Cities:	**EPW File Name:**
Lund	SWE_SN_Lund.Sol.026330_TMYx.2009-2023
Stockholm	SWE_ST_Stockholm.024850_TMYx.2009-2023
Luleå	SWE_NB_Lulea.AP.021860_TMYx.2009-2023

For the analysis of direct solar hours, the Ladybug tool was employed, utilising the Radiance simulation engine. For the analysis of ASE, sDA, UDI_a, and Average Illuminance, CS was used within the EnergyPlus simulation environment. Both simulation tools used the same three-dimensional model, although different sensor grid configurations and settings were applied for each. The simulation settings for each tool are presented in the Table 6 and Table 7, respectively.

Table 6: Simulation settings for Ladybug (Radiance).

Settings:	**Values:**
Type	Direct Sun Hours
Analysis Period	1 Year

Vector	LB Sun-Path
Output	Annual direct sun hours (H)

Table 7: Simulation settings for CS (EnergyPlus).

Settings:	**Values:**
Type	CS Daylight Availability - Custom
Occupancy Schedule	occResidential (annual)
Assessment Schedule	EN-17037
Ambient Bounces	12
Ambient Samples	4000
Sky Divisions	Continuous
Target lux	300
Supplemental lux	100
Excessive lux	3000
Output	ASE (%), sDA (%), UDI_a (%), Average Illuminance (lx)

3.2.6.2 Sensor grid

For the direct solar hours analysis, the outer envelope of the selected building was considered, encompassing all facades and the roof surface. A sensor grid size of six divisions was applied to each surface in Ladybug to balance computational efficiency with result accuracy. The sensor grid placement and the corresponding simulation output are illustrated in Figure 12 and Figure 13, respectively.

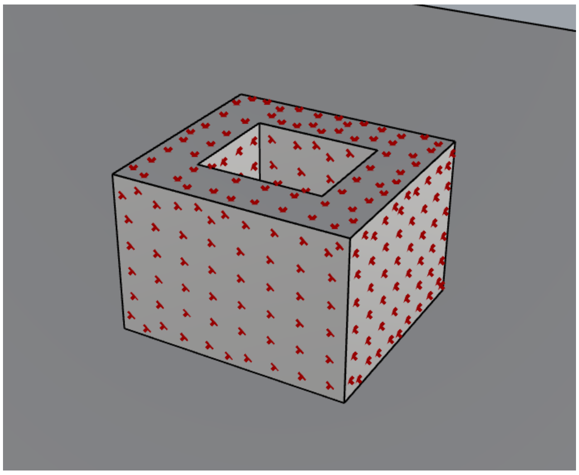


Figure 12:Ladybug sensor grid-placement on exterior surface.

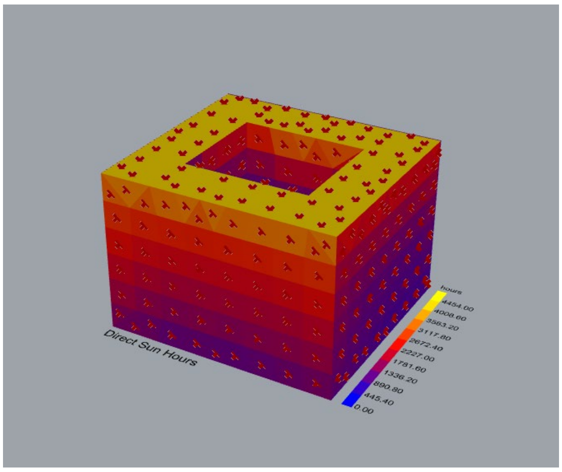


Figure 13:Ladybug sensor grid-simulation result on exterior surface.

For the sunlight access and diffuse daylight analysis of interior spaces, sensor grids were placed at working-plane height using CS. The grids were positioned at a level of 0.85 meters above the finished floor level across the full occupied floor area of each floor. Separate grids were generated for every floor, distinguishing between street-facing rooms and courtyard-facing rooms, with a sensor spacing of 0.5 meters. This ensured sufficient spatial resolution relative to the floor plate dimensions, as illustrated in Figure 14, where the white dots represent the sensor grid points. The resulting colour heatmap output from a representative simulation run is shown in Figure 15, where red indicated high values and blue indicated low values.

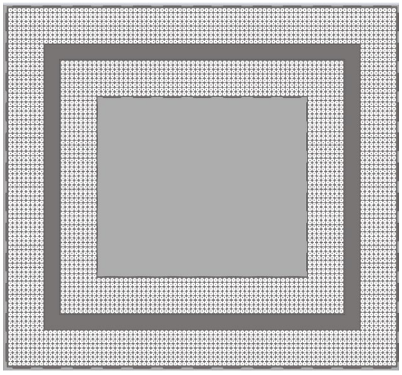


Figure 14:CS sensor grid-placement in interior space.

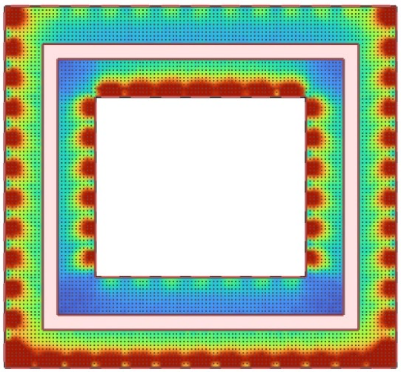


Figure 15:CS sensor grid-simulation result in interior space.

3.2.6.3 Surface materials and reflectance

Interior and exterior surface materials were assigned from the CS material library to represent realistic Swedish residential construction. Reflectance values were selected based on the recommendations by Dubois et al., (2025) for climate-based daylight simulation. These materials and their corresponding VLR values are presented in Table 8.

Table 8: Surface Material Properties.

Surface	Material Selected	VLR
Ceiling	Ceiling LM83	70.0%
Wall	Grey Wall Tile	57.9%
Floor	Wood Floor 2	29.3%
Facade	Light Yellow Brick	58.3%
Ground	Concrete Block Barrier	23.7%
Window	Starphire – Sungate 400 (3)	71.0%

The light-yellow brick facade material was adopted to represent a common Swedish residential construction style. The reflectance value of Concrete Block Barrier ground-surface was selected to represent typical urban paving in Swedish cities.

3.2.6.4 Window configurations

The study by Bülow-Hübe (2001) documented the window assemblies commonly used in Sweden, including their thermal performance and market prices. This study was used as a reference for window selection in the simulation. As the exact glazing assembly was not directly available in the CS material library, a closely matching assembly was selected from the database. The selected assembly was intended to reflect the properties of a typical Swedish window. The properties of both the selected CS library window and the recommended typical Swedish window are presented in Table 9. The glazing layer assemblies for each type are illustrated in Figure 16 and Figure 17, for reference.

Table 9: Comparison between simulation and recommended window properties.

Glazing Name:	**CS Library Window:** *Starphire + Sungate 400*	**Typical Swedish Window:** *T4-12-e10Ar*
Glazing Type:	Triple	Triple
U-value (W/ (m2.K):	1.05	1.12
SHGC (%):	60.5	57
T_{vis} (%):	71.3	78

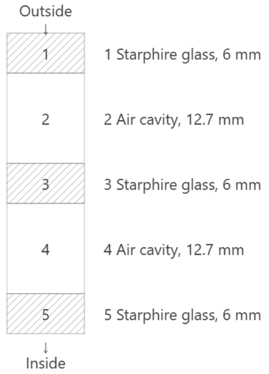


Figure 16: Layer assembly of CS library window.

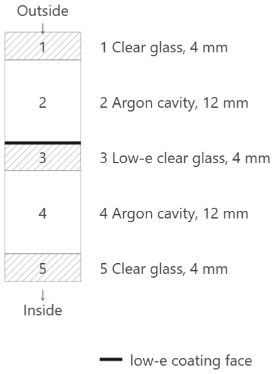


Figure 17: Layer assembly of Typical Swedish window.

4 Results

The results of the study are organised into several sections, with each section examining the influence of the independent variables - both individually and in combination - on the dependent variables. The emphasis is placed on comparing the lower, middle, and upper levels of each building type, as these represent the best-performing, intermediate, and worst-performing cases within each scenario. This approach ensures that the full performance range is captured and systematically analysed.

4.1 Sunlight access simulation

A total of 192 simulations were evaluated for both cumulative direct solar hours and ASE to examine how street orientation, street width, building height, and latitude influence sunlight access in residential buildings. Variations in the independent variables resulted in a redistribution of solar exposure across facades with different orientations. Consequently, the observed effects are interpreted as a redistribution of solar access across the building envelope rather than a change in the total amount of solar energy available to the building.

4.1.1 Annual direct solar hour

The total direct solar hours, presented in Figure 18, represent the cumulative sum of exposure across all facade surfaces and the roof. Figure 18 shows that a consistent pattern emerged across all three cities for the four tested street-orientation angles. The 90° orientation produced the highest total solar hours in every city, followed closely by the 0° orientation, with only a marginal difference between them. In contrast, the 30° and 60° orientations yielded the lowest totals across all cities and building configurations. The results also indicate a general decline in direct solar hours across all scenarios as latitude increases: Lund recorded the highest values, followed by Stockholm, and then Luleå. This trend is illustrated in Figure 18, where each box and whiskers show the distribution of values across all building types and street widths for each orientation angle, shown separately for each city.

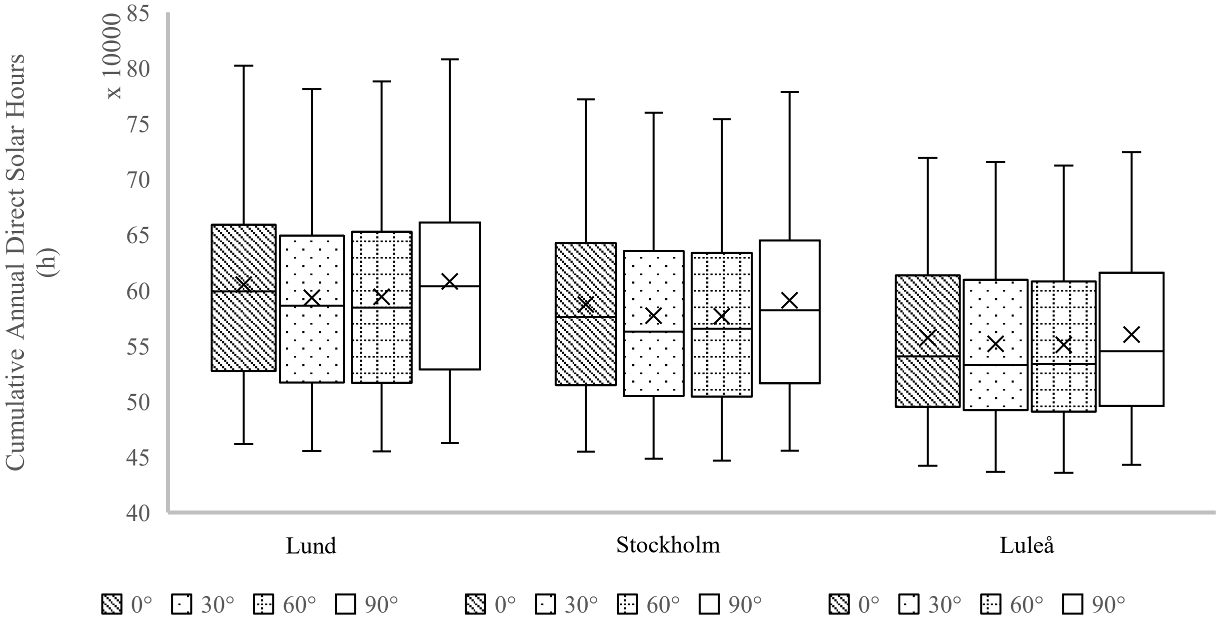


Figure 18: Cumulative total annual direct solar hours across all orientation for each city

Similarly, Figure 19 illustrates the impact of building height and street width on direct solar hours intensity, calculated as the cumulative density, where total direct solar hours were divided by the total building envelope area, for each orientation angle in each city. The results reveal a clear trend: an increase in building height resulted in a decrease in direct solar hours per square metre. In contrast, increasing street width led to higher direct solar hours per unit of envelope area; however, this effect diminished with increasing latitude.

When all independent variables were considered together, a three-floor building located along a 20 m-wide street oriented at 90° in Lund received the highest annual direct solar hours per square meter of building envelope. Conversely, a 12-floor building along a 7.5 m-wide street oriented at 30° in Luleå recorded the lowest values. For reference, Table 14 in the Appendices presents the cumulative annual direct solar hours across all simulated scenarios in the form of a colour/gradient-coded heat map.

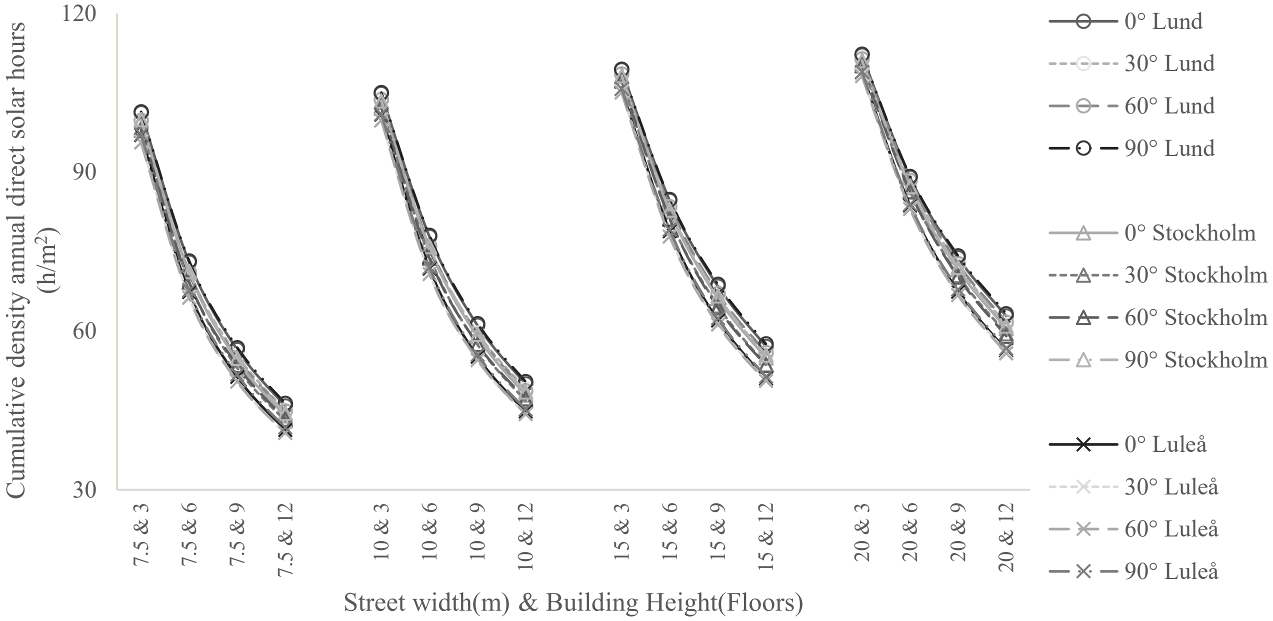


Figure 19: Cumulative density annual direct solar hours across all building type and street width for each city.

4.1.2 Annual sunlight exposure (ASE)

The impact of street orientation, street width, building height, and latitude on sunlight access at the individual floor level was investigated through a series of simulations. ASE was calculated indoors and defined as the percentage of an analysis area that exceeded a direct sunlight illuminance threshold of 1000 lux for more than 250 hours per year. The ASE analysis was used to identify conditions of excessive direct sunlight within interior spaces and to indicate a potential risk of glare or visual discomfort (IES, n.d.). According to EN 17037, a recommended ASE threshold of 10% is defined. Values below this threshold indicate low sunlight exposure, whereas values exceeding it suggest a high likelihood of glare occurrence.

The results of these simulations are presented in Figure 20 and Figure 23, in which each floor was treated as an independent case across 16 street scenarios for each building type in each city. No aggregation of floor-level data was applied. Instead, the ASE of each floor was assessed individually across the four orientation angles at each street width, thereby allowing the full vertical gradient, and its response to geometry and latitude, to be examined. However, for ease of presentation, only the lower, middle, and top floor levels of each building type are shown in the graphs. The best- and worst-performing cases are presented in Table 10 for comparison across each city.

Table 10: Best and worst scenarios across each city based on ASE values.

Performance Level	**Scenario Category**	**Lund**		**Stockholm**		**Luleå**	
		Orientation	**ASE (%)**	**Orientation**	**ASE (%)**	**Orientation**	**ASE (%)**
Best	Top Floor	90° & 20m (all building types)	54.9	90° & 20m (all building types)	57.8	90° & 20m (all building types)	61.8
	Lower Floor	60° & 20m (3-floor building type)	34.3	60° & 20m (3-floor building type)	33.9	60° & 20m (3-floor building type)	33.0
Worst	Top Floor	0° & 7.5m (all building types)	43.0	0° & 7.5m (all building types)	43.8	0° & 7.5m (all building types)	44.8
	Lower Floor	all orientations & 7.5m (6, 9, and 12-floor building types) all orientations & 10m (9 and 12-floor building types)	0.0	all angles & 7.5m and 10m (6, 9, and 12-floor building types)	0.0	all angles & 7.5m,10m and 15m (6, 9, and 12-floor building types)	0.0

A clear trend emerged when the simulation results were analysed in relation to street orientation angle and street width, as shown in Figure 20-Figure 23. Across all three cities, at street widths of 7.5 m and 10 m, the lower floors of nine-floor and 12-floor buildings recorded 0% ASE across all tested orientations, indicating that orientation had no measurable effect at these levels. In Luleå, this pattern extended to 15 m street widths. Under narrow (7.5-m and 10-m) street conditions, the 60° orientation, and to a lesser extent the 30° orientation, consistently produced the lowest ASE values at the lower floors, whereas the 0° and 90° orientations performed slightly better. At the middle floors of taller buildings under 15-m and 20-m street widths, the transition zone widened and the influence of orientation became more variable. However, for the three-floor building type, the middle floors across all street widths, as well as the lower floors under wider (15-m and 20-m) street conditions, showed that the 60° orientation became competitive or, in some cases, emerged as the best-performing orientation.

The upper floors consistently recorded higher ASE values across all scenarios and exhibited the largest absolute effect of orientation of any floor. Across all building types and cities, the 0° and 90° orientations consistently produced the highest ASE values at the top floors, while the 30° and 60° orientations consistently produced the lowest. The effect of orientation at the top floor was most pronounced in Luleå, which is due to the lower solar altitude angle, resulting in increased direct solar radiation on vertical facade surfaces and reduced self-shading from adjacent building elements.

Lund recorded the highest ASE values at the lower and middle floors, followed by Stockholm, with Luleå recording the lowest. At the upper and top floors, this ranking was reversed: Luleå recorded the highest ASE values, Stockholm intermediate values, and Lund the lowest across all scenarios and building types.

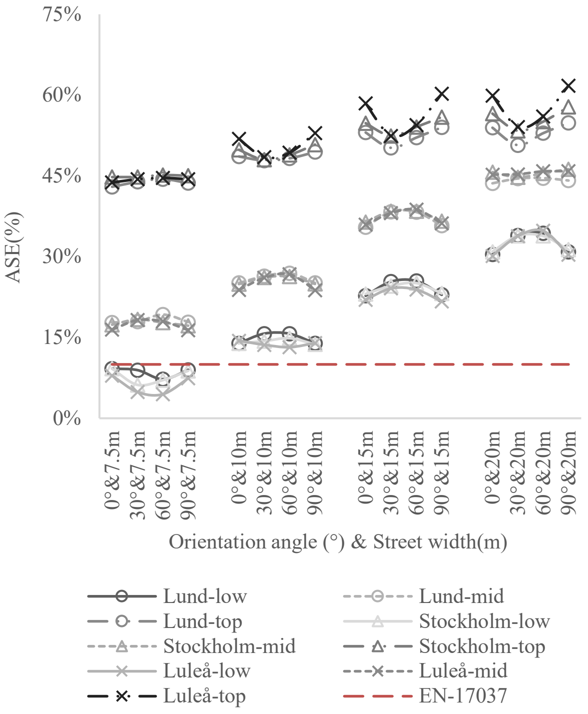


Figure 20: ASE of three-floor building type

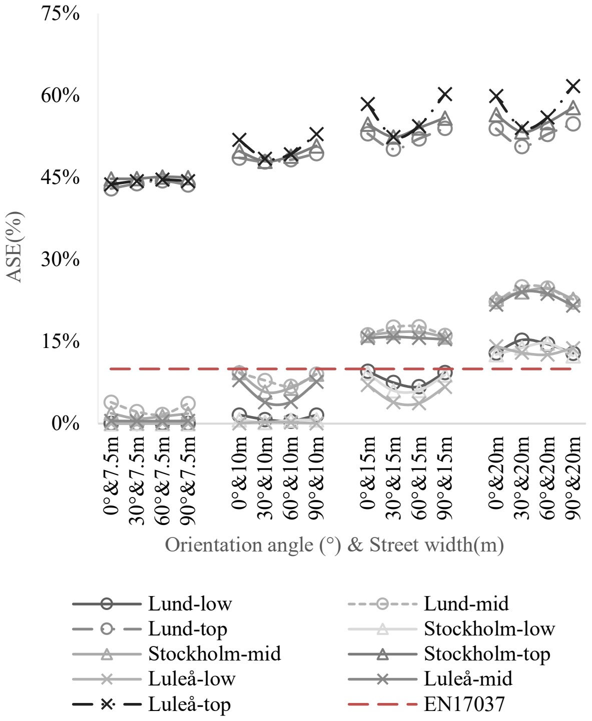


Figure 21: ASE of six-floor building type

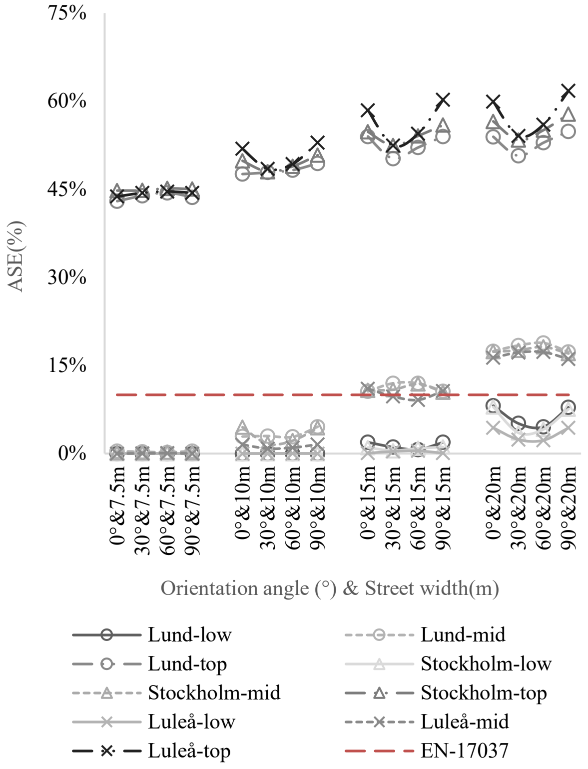


Figure 22: ASE of nine-floor building type

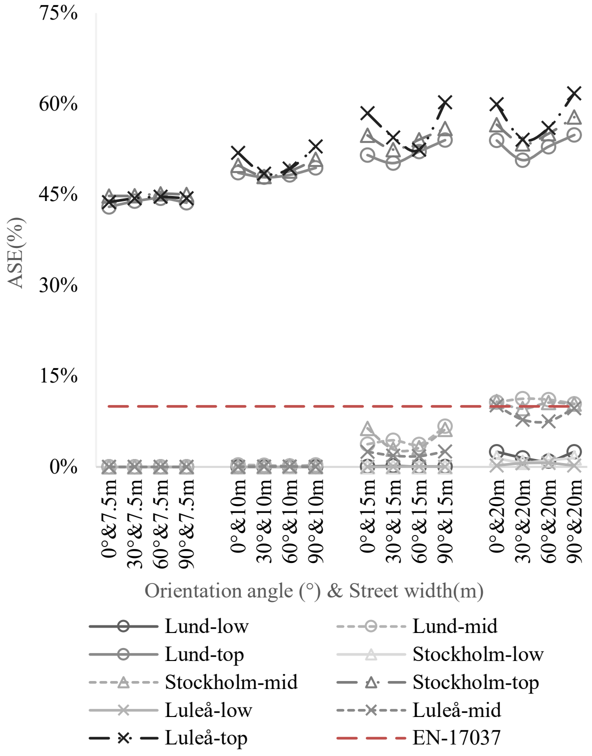


Figure 23: ASE of 12-floor building type

4.2 Daylight access simulation

To investigate diffuse daylight access, a series of daylighting simulations was conducted using CS across 192 scenarios. Variations in the independent variables resulted in a redistribution of daylight within interior spaces across different facade exposures. Overall, these variations defined the extent of daylight penetration into the habitable spaces of the simulated buildings. The results of this simulation series are presented in the following subsections with respect to three performance metrics: sDA, UDI_a, and Average Illuminance.

4.2.1 Spatial daylight autonomy (sDA)

Spatial Daylight Autonomy (sDA) is an IES-standardised metric that measures the percentage of an interior space receiving sufficient daylight (≥ 300 lux) for at least 50% of the occupied hours. It is primarily applied to regularly occupied spaces and serves as an indicator of occupant satisfaction with natural light, as well as the potential to reduce reliance on electric lighting (IES, n.d.). Additionally, sDA supports the optimisation of shading strategies by balancing daylight availability while limiting the risks of glare and excessive solar heat gain. In accordance with EN 17037, an sDA value of 55% is recommended. Values above this threshold represent high daylight availability, while values below it indicates a greater reliance on electric lighting.

Consistent with the latitudinal gradient across the three cities, Lund recorded the highest sDA values, followed by Stockholm, and then Luleå, across all building types, street widths, and orientation angles. While the difference between Lund and Stockholm was modest, the gap between Lund and Luleå was larger, reflecting the limited annual daylight availability at higher latitudes. In Luleå, the 300-lux threshold was more difficult to achieve on an annual cumulative basis, even under conditions of wider streets and minimal obstruction. The proportion of total number of floors, across all scenarios, achieving high sDA and low sDA for each city is presented in Table 11. These results indicate a clear shift in the sDA distribution toward lower values with increasing latitude, with Luleå exhibiting the highest share of poorly daylit floor conditions among the three cities.

Table 11: Proportion of floors achieving high and low $sDA_{300\ lx,\ 50\%}$ across all scenarios by city.

	$sDA_{300\ lx,\ 50\%} \geq 55\%$	$sDA_{300\ lx,\ 50\%} < 30\%$
Lund	65.0 %	22.5%
Stockholm	60.4%	24.2%
Luleå	55.8%	27.5%

The simulation results reveal a clear vertical pattern across all three cities. The sDA values for all floor levels in all buildings along a 10-m wide street, comparing street-facing and courtyard-facing rooms in Lund, Stockholm, and Luleå, are presented in Figure 24. The results indicate that lower floors receive significantly less daylight, and this effect becomes more pronounced as building height increases.

In three-floor buildings, all floors perform well in terms of sDA, including both street-facing and courtyard-facing rooms. The ground floor already achieves high sDA values, ranging from approximately 85% in Luleå to around 93% in Lund. These findings suggest that low-rise courtyard buildings can achieve adequate daylighting even at the ground level under narrow street conditions.

As building height increased, this pattern changed significantly. In six-floor buildings, sDA values at the ground floor declined across all cities. In nine-floor buildings, the ground floor experienced a further reduction in daylight availability, and in 12-floor buildings, sDA values decreased to 13-18%. These results indicate that the lower floors in taller courtyard buildings receive insufficient daylight.

A comparison between the top and bottom floors highlights an increasing disparity with building height. In three-floor buildings, the difference between the top and ground floor is small. However, in 12-floor buildings, the top floor can receive more than five to seven times the daylight of the ground floor. This effect is more pronounced in northern cities, where lower solar angles and longer shadows further reduce daylight availability at lower levels.

Street-facing floors consistently recorded higher sDA values than courtyard-facing floors at every level, with the greatest differences observed at the lower floors. This can be attributed to the self-shading effect of the courtyard block typology, which significantly restricts sky exposure for interior-facing rooms, particularly at corner locations. While the outer-facing rooms achieved high sDA values at the upper floors, the courtyard-facing spaces did not reach similar levels and remained consistently lower across all three cities.

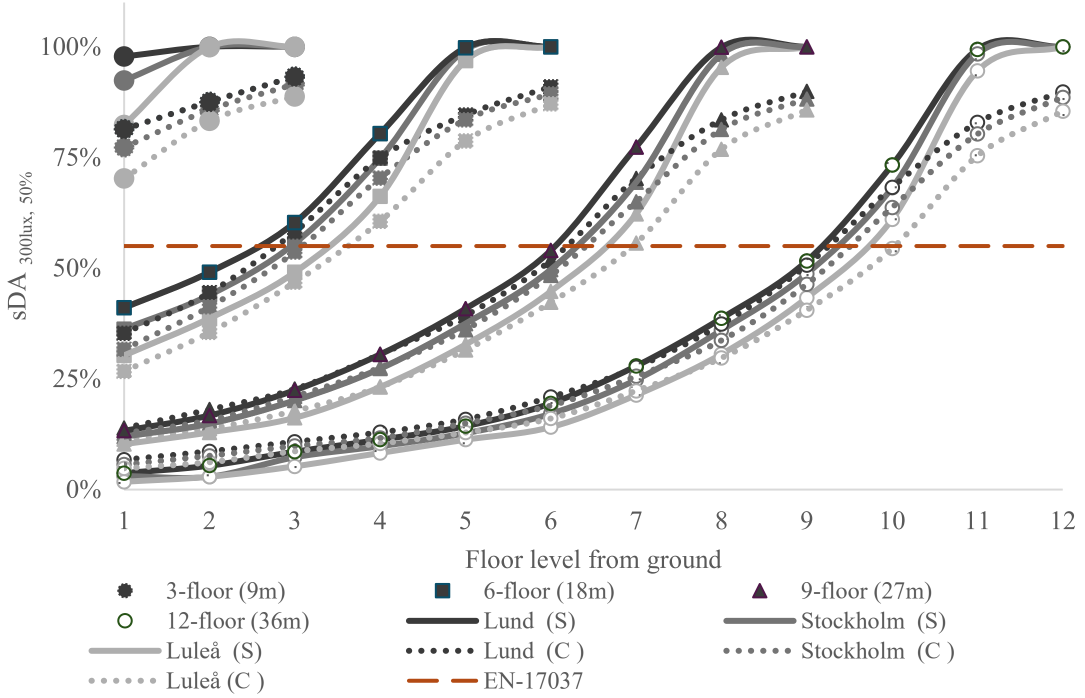


Figure 24: sDA Distribution across Cities for a 10 Meter Street Width.

Street width exhibited the strongest influence on sDA values for street-facing rooms, particularly at the lower floors, where sky exposure is most constrained by opposing buildings. The results show an increase in sDA with increasing street width across all building types and all three cities. This trend is illustrated in Figure 25, which presents the sDA values for all the floors of a 12-floor building in Lund at a 0° orientation angle, across increasing street widths (7.5 m, 10 m, 15 m, and 20 m) for both street-facing (S) and courtyard-facing (C) rooms.

On the street-facing facades, street width directly influences the amount of daylight reaching each floor. Wider streets reduce obstruction from the opposing building, allowing greater quantities of diffuse daylight to penetrate the lower floors. At the ground floor, increasing street width from 7.5 m to 20 m resulted in an increase in sDA from near zero to 49%. Toward the upper floors, the influence of street width diminished, as these levels received increasingly unobstructed daylight. In contrast, sDA values on the courtyard-facing facades remained unaffected by street width, which is an expected result. This pattern was consistent across all building types, orientation angles, and cities.

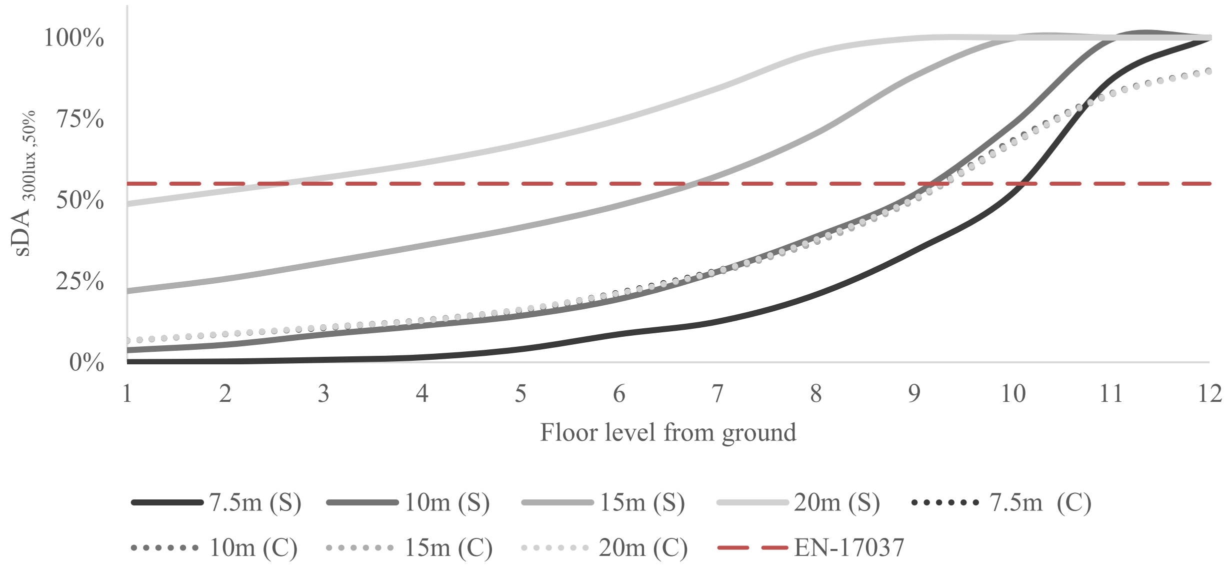


Figure 25:Effect of Street width on sDA for 12-floor building at 0°orientation.

To evaluate the influence of street orientation on daylight access, the average sDA values of the lowest floor (Floor 1) for all building types were plotted against the height-to-width (H/W) ratio of the urban canyon across four orientations, as shown in Figure 26. The resulting curves for the 0°, 30°, 60° and 90° orientations followed nearly identical, parallel trajectories across the mid-range of H/W ratios, with differences between orientations remaining minimal (approximately 2-3%) within each city. These results indicate that street orientation has a negligible influence on sDA.

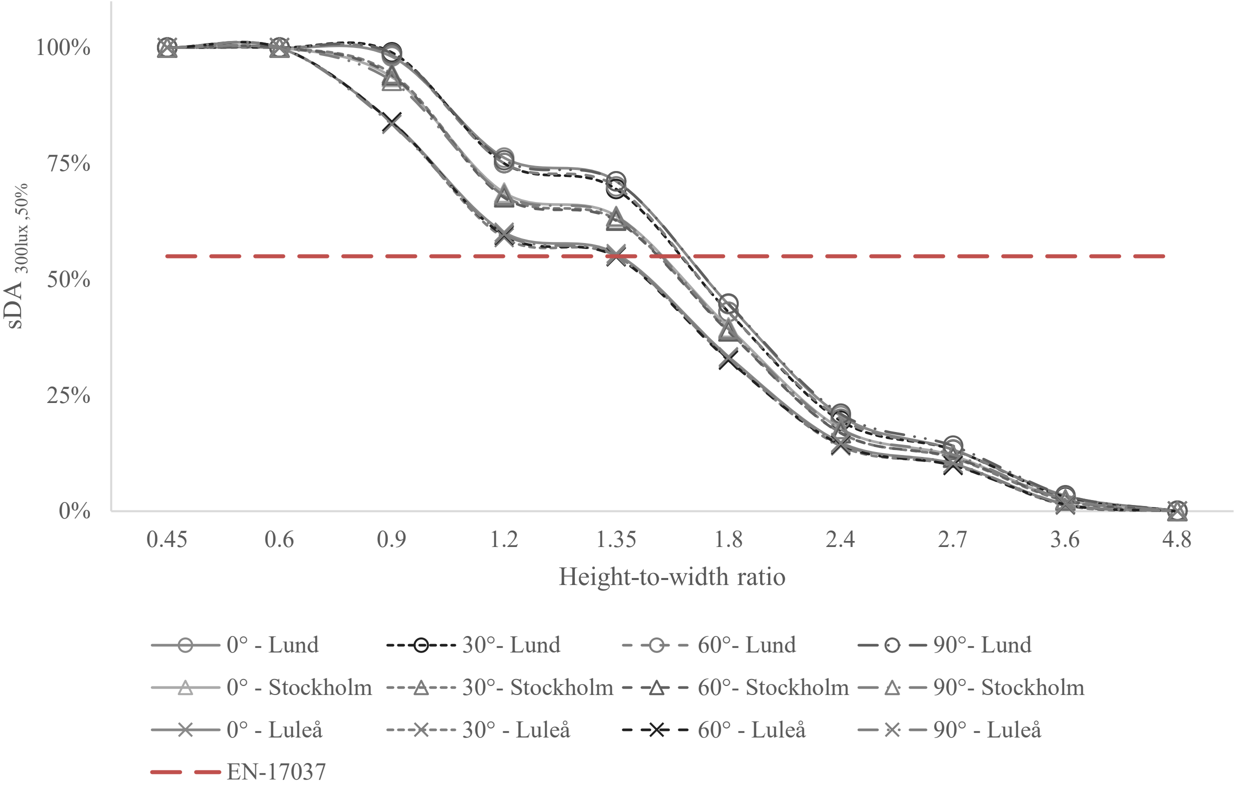


Figure 26: Effect of H/W ratio on sDA of lowest floor (Floor-1) across all orientations.

Additionally, a clear exponentially decreasing relationship was observed between sDA and the height-to-width (H/W) ratio, with sDA values decreasing as the H/W ratio increased across all cities. Higher H/W ratios correspond to taller buildings and narrower urban canyons, which impose greater obstruction to daylight access. This further highlights the H/W ratio as the dominant parameter governing daylight availability. It was also observed that, while sDA values at the lowest floor decreased with increasing latitude, the magnitude of this latitudinal difference diminished as the H/W ratio decreased.

4.2.2 Useful daylight illuminance $_{\text{autonomous}}$ (UDI$_a$)

To investigate the impact of street orientation and street width on daylighting performance, a series of simulations using CS was conducted for each floor across all 16 scenarios in each city. UDI$_a$ was used as one of the key performance metrics in this analysis and represents the percentage of occupied time during which indoor daylight illuminance at the working-plane level falls within the range of 300–3000 lux, a range considered optimal for performing tasks without electric lighting (IES, n.d.). According to recommended guidelines, UDI$_a$ values above 80% are considered suitable for focused tasks, while values above 50% are generally acceptable for habitable spaces (Acosta et al., 2019).

The UDI$_a$ results, as presented in Figure 27 for Lund, reveal a consistent pattern across all building types, with values increasing with floor height. The ground floor recorded the lowest UDI$_a$ values in every building, and each successive floor performed better than the one below. Examination of the individual floor-level data further indicated that the effect of street orientation was consistently small, though not entirely negligible. In contrast, the influence of increasing street width showed an amplifying trend, becoming more pronounced with increasing building height. These patterns were also observed in Stockholm and Lulea, as shown in Figure 44Figure 45 in the Appendices. In addition, a clear geographical gradient was identified, with Lund consistently outperforming Stockholm, and Stockholm consistently outperforming Luleå, at every floor across all scenarios. The best- and worst-case scenario for each city are presented in the Table 12, for comparative analysis. It should be noted that both the best- and worst-performing scenarios occur within the 12-floor building type.

Table 12: Best- and worst-case scenarios for each city based on UDI$_a$ performance.

	Absolute Best Value (%)	**Floor, Building, Scenario**	**Absolute Worst Value** (%)	**Floor, Building, Scenario**
Lund	72.1	12-Floor, Floor-12, 0° & 20m	8.5	12-Floor, Floor-1, 0° & 7.5m
Stockholm	70.5	12-Floor, Floor-12, 0° & 20m	7.3	12-Floor, Floor-1, 0° & 7.5m
Luleå	66.8	12-Floor, Floor-12, 0° & 20m	5.6	12-Floor, Floor-1, 0° & 7.5m

In the three-floor building, the floor-to-floor gradient was relatively shallow. The effect of street width was evident at the lower floors but diminished rapidly toward the upper levels. For the six-floor building, the influence of street width was pronounced at the three lowest floors and gradually weakened toward the upper floors. In the nine-floor building, both the lower and middle floors exhibited high sensitivity to street width. At street widths of 7.5 m and 10 m, the middle floors barely exceeded the 50% UDI$_a$ threshold, whereas under wider street conditions (15 m and 20 m), only the lowest floors (Floors 1 and 2) showed similarly low values across all cities.

This disparity became more pronounced in the 12-floor building, where approximately two-thirds of the floors remained below the 50% UDI$_a$ threshold in Lund and Stockholm, and an even larger proportion in Luleå, under narrow street conditions (7.5 m and 10 m). Under wider street widths (15 m and 20 m), this limitation was largely confined to the lowest two floors across all cities. The effect of street orientation was most detectable at the lower floors of taller buildings under narrow street conditions. Across all cities and building types, the cardinal orientations (0° and 90°) tended to produce marginally higher UDI_a values than the diagonal orientations (30° and 60°), with the 30° orientation most frequently recording the lowest UDI_a values, followed by the 60° orientation.

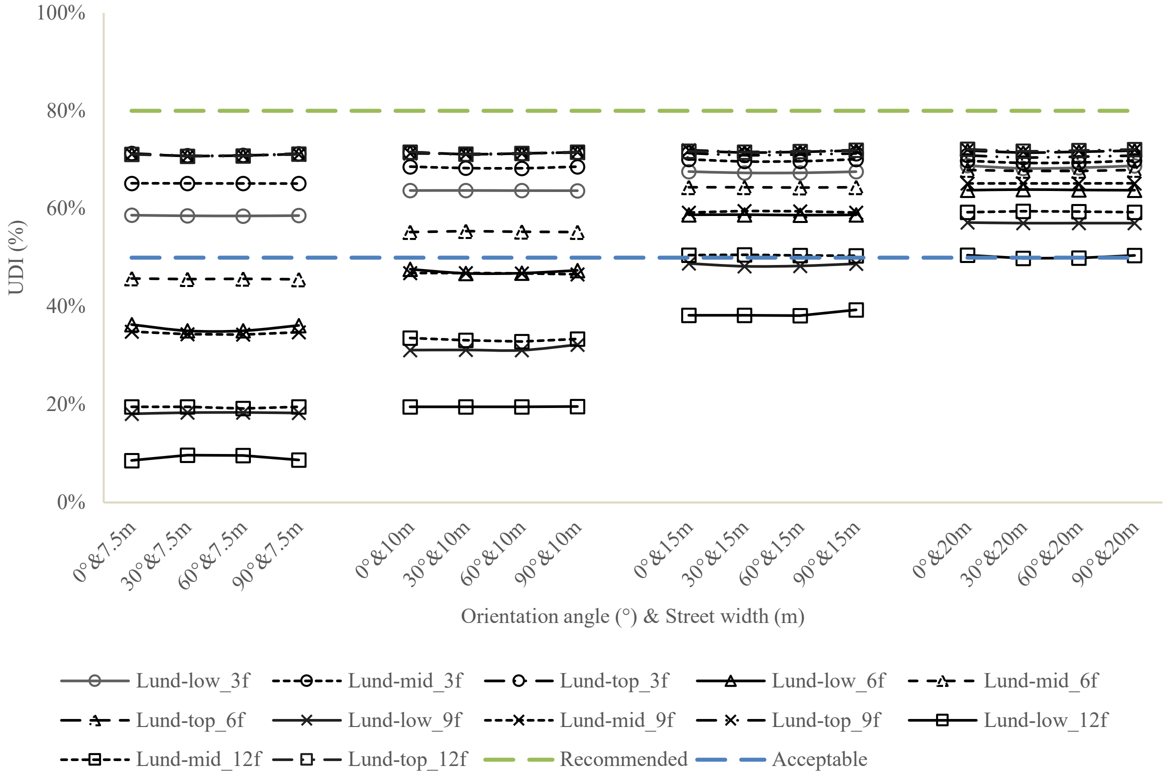


Figure 27: UDI_a of all building type across all orientation scenarios for Lund city.

4.2.3 Average illuminance

This section presents the average illuminance results obtained from CS daylight simulations for all building types across 16 orientation scenarios in three Nordic cities. Average illuminance represents the mean density of daylight incident per unit surface area and was measured at the working-plane level, defined as 0.85 m above the floor, over all occupied hours throughout the year. The average illuminance results were analysed to examine the influence of street orientation, street width, building height, and latitude on the distribution of daylight across all floors of the simulated buildings. All analysed values were evaluated at the floor level and further differentiated between street-facing and courtyard-facing zones, thereby capturing variations in daylight performance across the full vertical and internal extent of the buildings.

The average illuminance results, presented in Figure 28 - Figure 31, exhibited consistent trends with varying magnitudes when analysed across all 16 scenarios for Lund. For ease of presentation, all floors of the three-floor building and selected representative floors (Floors 1, 3, 6, 9, and 12) of the 12-floor building are shown. Similar trends were observed for Stockholm and Luleå. However, when compared across latitudes, as shown in Table 13, Lund, as the southernmost city, consistently recorded the highest average illuminance values across all building types and orientations, followed by Stockholm, while Luleå recorded the lowest values.

Table 13: Summary of mean illuminance (lx) across all scenarios and building types for each city.

	Street-Facing Rooms			**Courtyard-Facing Rooms**		
	Lowest Value (lx)	**Highest Value** (lx)	**Mean** (lx)	**Lowest Value** (lx)	**Highest Value** (lx)	**Mean** (lx)
Lund (55.7°N)	112.4	2165.5	1101.0	194.5	1508.9	830.9
Stockholm (59.3°N)	101.1	2147.9	1066.5	1503.4	161.2	814.2
Luleå (65.6°N)	86.1	2098.2	999.0	1478.9	132.9	765.1

Building height exhibited a consistent inverse relationship with average illuminance at the lower floors across all three cities and all scenarios. Average illuminance increased with floor height, with each successive floor recording higher values than the one below. The upper floors of all building types showed similarly high average illuminance levels, whereas the lower floors of taller buildings experienced the most pronounced reductions.

Among all tested parameters, street width exhibited the strongest influence on average illuminance, as illustrated in Figure 28 and Figure 29 . As street width increased, average illuminance values in street-facing rooms increased accordingly, while remaining largely unchanged in courtyard-facing rooms, which was an expected results as the courtyards remain identical. However, the magnitude of this effect in the street-facing rooms diminished with increasing floor height. Figure 28 and Figure 29 illustrate this trend by comparing illuminance values across different floor levels of three-floor and 12-floor buildings in Lund.

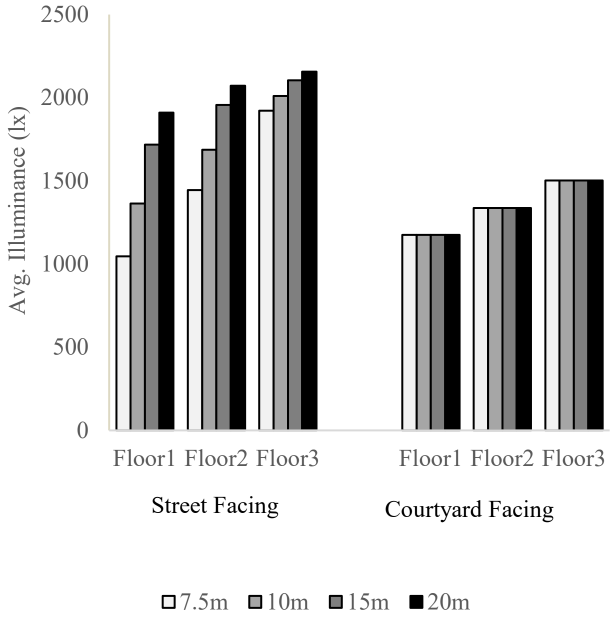


Figure 28: Average Illuminance for 3-floor building in Lund across all street width.

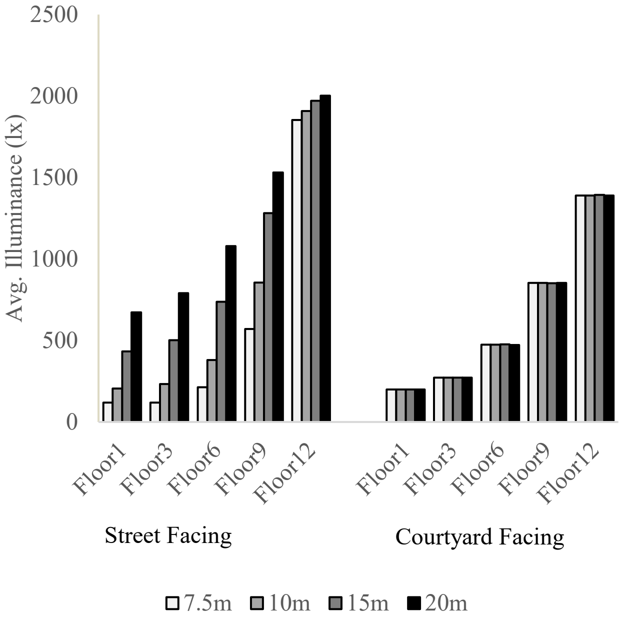


Figure 29: Average Illuminance for 12-floor building in Lund across all street width.

Street orientation angles (0°, 30°, 60°, and 90°), as illustrated in Figure 30 and Figure 31, exhibited a comparatively minor influence on average illuminance relative to the dominant effects of street width and building height across all building types. Figure 30 and Figure 31 present the average illuminance values at different floor levels for three-floor and 12-floor buildings in Lund under varying street orientations, with the data categorised into street-facing and courtyard-facing rooms. The 30° and 60° orientations occasionally yielded slightly higher average illuminance values than the 0° and 90° orientations; however, the differences between orientation angles were small compared to the overall range introduced by variations in street width. This pattern was also observed in Stockholm and Luleå. Across all cities and building types analysed, courtyard-facing rooms consistently recorded substantially lower average illuminance values than street-facing rooms.

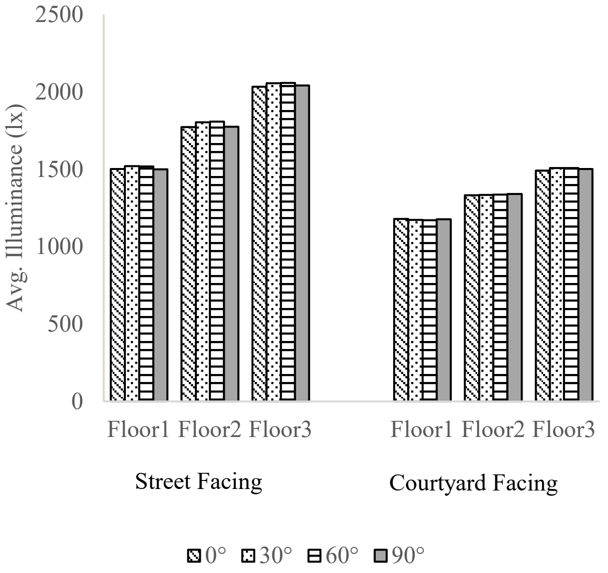


Figure 30: Average Illuminance for 3-floor building in Lund across all street orientation.

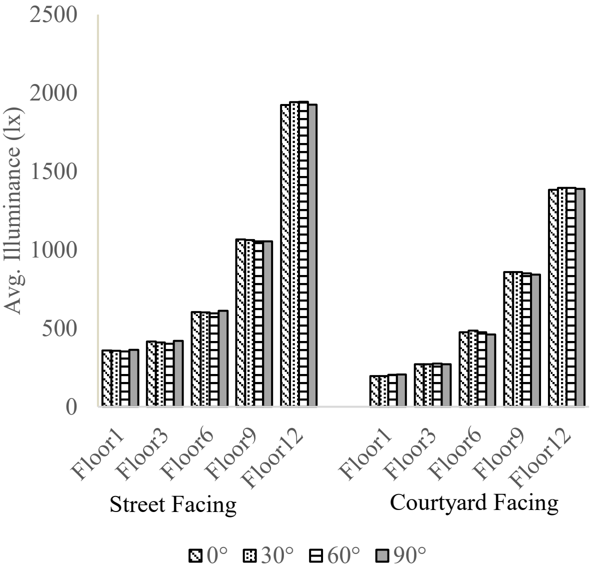


Figure 31: Average Illuminance for 12-floor building in Lund across all street orientation.

5 Discussion

This study examines how street orientation, street width, building height, and latitude influence sunlight and daylight access in residential courtyard block typologies across three Nordic cities. The main findings are discussed below in relation to the research questions.

5.1 Effect of street orientation, building height, and street canyon width on sunlight and daylight availability

The first research question (RQ1) asked: "How does street orientation influence sunlight access in residential buildings located in Nordic climatic conditions characterised by high latitude, low solar angles, and strong seasonal daylight variation?" The results indicate a non-linear relationship between sunlight access and street orientation. When street orientation was altered in 30° increments (from 0° to 90°), sunlight access followed a non-linear pattern, initially declining from its highest level to its lowest performance at diagonal orientations (30° and 60°), before increasing again at the cardinal orientation. However, because the differences between the extreme orientation angles are marginal, street orientation exerts a negligible influence on cumulative sunlight performance across facades and interior spaces in courtyard building typologies. This finding is particularly relevant in Nordic climatic conditions, where the sun remains at a low angle for much of the year. The orthogonal geometry of the built form further moderates the effect of orientation, rendering it less influential on sunlight access than the width and height of the surrounding urban space.

The second research question (RQ2) examined the influence of street orientation on daylight availability in residential blocks with varying building heights and street canyon widths. The results once again indicate that street orientation has a negligible effect on daylight availability, as measured by sDA, UDI_a, and average illuminance. However, the influence of orientation becomes slightly more pronounced on the lower floors of taller buildings, that is, under higher height-to-width (H/W) ratios.

For both sDA and UDI_a, the impact of street orientation follows a non-linear pattern, with marginally higher performance observed at the cardinal orientations (0° and 90°) compared to the diagonal orientations (30° and 60°), with 30° frequently recording the lowest values. In contrast, cumulative average illuminance exhibits an inverse trend, whereby diagonal orientations perform marginally better than cardinal orientations. This difference can be attributed to the low solar altitude prevailing for most of the year in Nordic contexts, combined with the relatively low illuminance threshold range (100–1000 lx) considered in the average daylight illuminance performance metric.

It is important to note that courtyard-facing illuminance values exhibit remarkably little variation across different orientation angles and street widths. This can be attributed to the fact that rooms facing the courtyard primarily receive daylight from the sky vault directly above the courtyard, which is largely unaffected by variations in external street geometry.

While south-facing facades demonstrably achieve higher levels of solar access, this advantage becomes less pronounced when performance is assessed at the scale of the entire building. For urban planners and designers, parameters such as street canyon width and building height therefore represent more critical design considerations than street orientation. This suggests that design efforts and regulatory frameworks may be more effectively directed toward controlling street width and building height rather than prescribing specific street orientations. These findings further indicate that orientation is more appropriately addressed at the building scale, rather than as a primary directive in urban planning.

5.2 Sunlight distribution across building floors

The third research question (RQ3) asked: How does sunlight distribution vary across different building floors when accounting for shading effects and facade exposure from adjacent buildings? The ASE results indicate that excessive sunlight constitutes a design concern equal in importance to insufficient daylight. Upper floors consistently receive high levels of direct sunlight, introducing risks of glare and overheating, whereas lower floors face the contrasting challenge of limited solar access.

This vertical imbalance suggests that a single design strategy cannot effectively address daylight and sunlight conditions across the full height of a building. Upper levels are therefore more likely to benefit from shading devices, reduced glazing areas, or solar-control glazing, while lower levels may require design interventions aimed at maximising available natural light, such as larger window areas and higher visual transmittance. In addition, reducing window size on upper floors increases the proportion of opaque facade surfaces, which can enhance light reflection toward lower floors; consequently, glare reduction at upper levels may indirectly improve daylight conditions on lower floors.

Accounting for this floor-to-floor gradient is essential for achieving both occupant comfort and balanced energy performance across the building section.

5.3 Comparison across the three Nordic cities

The fourth research question (RQ4) asked: How do the effects of street orientation differ across the three Nordic cities of Lund, Stockholm, and Luleå, given their distinct latitudes? The results demonstrate that geographical location exerts a substantial influence on daylight performance, including both direct and diffuse components. Lund, located at 55.7°N, consistently achieves the highest daylight performance across all simulated configurations, while Stockholm, at 59.3°N, performs at a moderate level, and Luleå, situated above 65.6°N, exhibits the weakest daylight conditions throughout.

This pattern is closely linked to latitude: as latitude increases, the sun remains lower in the sky, casting longer shadows and reducing the intensity of daylight reaching building surfaces. Higher latitudes are also characterised by shorter days and longer nights around the winter solstice, further limiting daylight availability. Notably, the performance gap between the three cities becomes more pronounced with increasing building height and decreasing street canyon width, indicating that the combined effects of urban geometry and latitude are not merely additive but compounding.

The practical implication is clear: design configurations that satisfy daylight requirements in Lund may prove insufficient in Stockholm, and even more so in Luleå, without substantial adjustments to building height, inter-building distance, or glazing dimensions. Consequently, building height and window-to-wall ratio should be treated as location-specific design parameters rather than universal values applicable across Nordic latitudes.

5.4 Design recommendations

Finally, the fifth research question (RQ5) addressed design recommendations to support early-stage urban planning decisions for residential areas in Nordic climatic conditions. The results indicate that, within Nordic residential planning, design efforts should be primarily directed toward controlling building height and street width rather than street orientation. Both parameters exert a stronger influence on daylight and sunlight performance across floor levels due to the compounding effects of urban geometry and limited solar availability. Consequently, they should be evaluated in relation to the specific solar conditions of each location, rather than according to a universal standard.

A more even distribution of daylight across floor levels can be achieved by regulating building height in proportion to street canyon width. At the building scale, upper floors may require measures such as solar control strategies and/or reduced glazing areas to mitigate glare and overheating, whereas lower floors may benefit from increased glazing areas to compensate for reduced daylight access. In addition, orienting buildings toward the south remains a relevant consideration at the building level, as it can provide a modest yet consistent improvement in solar access across all floor levels.

6 Conclusion

This study examined how building height, canyon width, orientation, and geographical location influence daylight and sunlight conditions in courtyard buildings across three Swedish cities. The key findings are summarized below:

- Street orientation has a negligible effect on sunlighting and daylighting in the courtyard typology in the three Swedish cities studied.
- Increasing building height amplifies the difference in daylight access between upper and lower floors, with the lowest levels having particularly poor daylighting in taller configurations.
- Canyon width emerged as the most influential factor, with wider street canyons consistently producing significantly better daylight conditions.
- Geographical location also proved to be important, with northern cities requiring more careful design considerations (e.g. larger distance between buildings, smaller buildings, etc) to achieve adequate daylight levels.
- A recurring vertical imbalance was observed, whereby lower floors experienced insufficient daylight while upper floors were exposed to excessive solar radiation. The most favourable conditions were generally found on the middle floors.

These findings offer practical guidance for early-stage design decisions in Swedish residential housing.

6.1 Limitations

This study focuses specifically on daylighting performance and does not account for other relevant aspects of building performance, such as indoor thermal comfort, energy use, life cycle cost (LCC), life cycle assessment (LCA), or passive solar heat gain analysis. The findings therefore reflect daylight and sunlight conditions alone and should not be interpreted as indicators of overall building performance.

The height range examined is limited to buildings between three and 12 floors, corresponding to approximately 9 m to 36 m; consequently, results outside this range cannot be directly extrapolated. Similarly, only the courtyard building typology is investigated. Other common urban forms, such as tower, slab buildings, and detached buildings, are not analysed, which limits the applicability of the findings to this specific geometry.

The material properties used in the simulations are based on standard industry values and literature references. However, real buildings may differ in material composition, and variations in surface properties can influence simulation outputs and, consequently, the interpretation of results. Furthermore, the parametric models are simplified; real urban environments typically involve irregular geometries, balconies, surrounding buildings, and vegetation, none of which were represented in the models used in this study.

Weather data were derived from Typical Meteorological Year (TMY) files, which represent average climatic conditions. As such, extreme weather events and projected future climate changes are not considered. In addition, the study focuses on three Swedish cities which, despite representing a range of latitudes, may not fully capture conditions in other regions or climates.

The analysis primarily addresses external, street-facing habitable spaces, while courtyard-facing facades are not fully evaluated in this part of the study. Moreover, only selected floor levels (1, 3, 6, 9, and 12) are considered for analysis and comparison. Finally, user behaviour, interior layout, and window operation patterns are not considered, even though these factors can significantly influence daylight perception and the actual use of natural light in practice.

6.2 Future Research

Future research could build on this study by integrating daylight analysis with detailed assessments of energy performance, thermal comfort, and solar heat gains. Such an approach would provide a more comprehensive understanding of how design decisions influence overall building performance, particularly in balancing useful daylight provision with the risk of overheating at upper floor levels.

Expanding the scope to include additional building typologies - such as slab blocks, point blocks, and mixed urban forms - would help determine whether the trends identified in this study are specific to courtyard buildings or more generally applicable. Furthermore, extending the range of building heights and street widths to include taller buildings and denser urban configurations would clarify the limits and transferability of the present findings.

The use of more detailed simulation models incorporating features such as balconies, shading devices, facade variations, glazing types, and surrounding buildings would enhance the realism of the analysis and bring the results closer to real-world design conditions. Investigating a wider range of material properties and facade configurations would further improve understanding of their influence on daylight availability and solar access. In addition, validating simulation results against empirical measurements from existing buildings would strengthen the reliability and robustness of the conclusions.

Incorporating climate change scenarios into future analyses would enable the assessment of how evolving weather patterns may affect daylight availability and solar exposure in Nordic cities over time.

Finally, translating these findings into practical design guidelines or early-stage planning tools would improve their applicability in professional practice, supporting architects and planners in making more informed decisions regarding daylight and solar access in residential design.

References

Acosta, I., Campano, M. Á., Domínguez, S., & Fernández-Agüera, J. (2019). Minimum daylight autonomy: A new concept to link daylight dynamic metrics with daylight factors. LEUKOS, 15(4), 251–269. https://doi.org/10.1080/15502724.2018.1564673

Antón, A. R., Belmonte, J. A., & González-García, A. C. (2016). Romans in the Near East: The orientation of Roman settlements in present-day Jordan. https://doi.org/10.5281/ZENODO.220914

Boeing, G. (2019). Urban spatial order: Street network orientation, configuration, and entropy. Applied Network Science, 4(1), 67. https://doi.org/10.1007/s41109-019-0189-1

Bournas, I. (2021.). Daylight compliance of multi-dwelling apartment blocks.

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

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

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

Boverket. (n.d.). Boverket's building regulations—Mandatory provisions and general recommendations (BBR). Retrieved February 1, 2026, from https://www.boverket.se/en/start/publications/2019/boverkets-building-regulations--mandatory-provisions-and-general-recommendations-bbr/

Boverket. (n.d.). Boverkets föreskrifter (2024:14) om ändring av Boverkets byggregler (2011:6)—föreskrifter och allmänna råd.

Brown, G. Z., & DeKay, M. (2014). Sun, wind, and light: Architectural design strategies. John Wiley & Sons.

Bülow-Hübe, H. (2001). Energy efficient window systems: Effects on energy use and daylight in buildings (Doctoral dissertation).

Bülow-Hübe, H., Dubois, M.-C., Hemphälä, H., Rogers, P., Söderlund, M., & Persson, M. (2022). Ljus—Dagsljus, solljus, utblick och belysning.

Climate.onebuilding.org. (n.d.). Retrieved May 4, 2026, from https://climate.onebuilding.org/default.html#gsc.tab=0

Compagnon, R. (2004). Solar and daylight availability in the urban fabric. Energy and Buildings, 36(4), 321–328. https://doi.org/10.1016/j.enbuild.2004.01.009

Czachura, A. (2023). Solar access indicators for urban planning.

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

Czachura, A., Kanters, J., Gentile, N., & Wall, M. (2022). Solar performance metrics in urban planning: A review and taxonomy. Buildings, 12(4). https://doi.org/10.3390/buildings12040393

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

De Luca, F., & Sepúlveda, A. (2021, September 1). Integrated analysis of daylight and solar access building requirements and performance in urban environments in Estonia. Building Simulation Conference 2021. https://doi.org/10.26868/25222708.2021.30278

Dubois, M.-C., Gentile, N., Laike, T., Mattsson, P., Bournas, I., & Alenius, M. (2025). Daylighting and lighting: Under a Nordic sky. In Open Books at Lund University. https://doi.org/10.37852/oblu.324

Formolli, M., Kleiven, T., & Lobaccaro, G. (2022). Solar accessibility at the neighborhood scale: A multi-domain analysis to assess the impact of urban densification in Nordic built environments. Solar Energy Advances, 2, 100023. https://doi.org/10.1016/j.seja.2022.100023

Formolli, M., Kleiven, T., & Lobaccaro, G. (2023). Assessing solar energy accessibility at high latitudes: A systematic review of urban spatial domains, metrics, and parameters. Renewable and Sustainable Energy Reviews, 177, 113231. https://doi.org/10.1016/j.rser.2023.113231

Forsberg, M., & de Souza, C. B. (2021). Implementing regenerative standards in politically green Nordic social welfare states: Can Sweden adopt the living building challenge? Sustainability, 13(2), 738. https://doi.org/10.3390/su13020738

Francart, N., Polycarpou, K., Malmqvist, T., & Moncaster, A. (2022). Demands, default options and definitions: How artefacts mediate sustainability in public housing projects in Sweden and Cyprus. Energy Research & Social Science, 92, 102765. https://doi.org/10.1016/j.erss.2022.102765

Garcia-Fernandez, B., & Omar, O. (2023). Sustainable performance in public buildings supported by daylighting technology. Solar Energy, 264, 112068. https://doi.org/10.1016/j.solener.2023.112068

Grimm, N. B., Faeth, S. H., Golubiewski, N. E., Redman, C. L., Wu, J., Bai, X., & Briggs, J. M. (2008). Global change and the ecology of cities. Science, 319(5864), 756–760. https://doi.org/10.1126/science.1150195

Hachem Vermette, C., Yadav, S., Brozovsky, J., Croce, S., Desthieux, G., Formolli, M., Grewal, K. S., Kanters, J., Lobaccaro, G., Manni, M., & Wall, M. (2024). Towards the development of legislative framework for solar neighborhoods. Frontiers in Built Environment, 10. https://doi.org/10.3389/fbuil.2024.1352844

Hraška, J., & Čurpek, J. (2024). The practical implications of the EN 17037 minimum target daylight factor for building design and urban daylight in several European countries. Heliyon, 10(1), e23297. https://doi.org/10.1016/j.heliyon.2023.e23297

Jin, Z., Chen, X., Rogers, P., Perez Morata, A., Rasmussen, H., & Gentile, N. (2025). Proposal for revised criteria for daylight provision in the European daylight standard based on calculations for Swedish multifamily residential buildings. Lighting Research & Technology, 57(6–7), 473–498. https://doi.org/10.1177/14771535241306970

Kanters, J., Gentile, N., & Bernardo, R. (2021). Planning for solar access in Sweden: Routines, metrics, and tools. Urban, Planning and Transport Research, 9(1), 347–367. https://doi.org/10.1080/21650020.2021.1944293

Kanters, J., & Wall, M. (2018). Experiences from the urban planning process of a solar neighbourhood in Malmö, Sweden. Urban, Planning and Transport Research, 6(1), 54–80. https://doi.org/10.1080/21650020.2018.1478323

IES VE. (n.d.-a). Lighting analysis. Retrieved May 3, 2026, from https://help.iesve.com/ve2021/lighting_analysis.htm

Littlefair, P. (2001). Daylight, sunlight and solar gain in the urban environment. Solar Energy, 70(3), 177–185. https://doi.org/10.1016/S0038-092X(00)00099-2

Liu, Y., Considine, B., & McNabola, A. (2024). Assessment of hygrothermal performance and mould growth risk in roofs of post-retrofitted non-dormer and dormer attic rooms with reduced ventilation. Building and Environment, 250, 111172. https://doi.org/10.1016/j.buildenv.2024.111172

Loibl, W., Vuckovic, M., Etminan, G., Ratheiser, M., Tschannett, S., & Österreicher, D. (2021). Effects of densification on urban microclimate—A case study for the city of Vienna. Atmosphere, 12(4), 511. https://doi.org/10.3390/atmos12040511

Magli, G. (2008). On the orientation of Roman towns in Italy. Oxford Journal of Archaeology, 27(1), 63–71. https://doi.org/10.1111/j.1468-0092.2007.00296.x

Manni, M., Formolli, M., Boccalatte, A., Croce, S., Desthieux, G., Hachem-Vermette, C., Kanters, J., Ménézo, C., Snow, M., Thebault, M., Wall, M., & Lobaccaro, G. (2023). Ten questions concerning planning and design strategies for solar neighborhoods. Building and Environment, 246, 110946. https://doi.org/10.1016/j.buildenv.2023.110946

Mukherjee, B., & Boubekri, M. (2025). Sustainable architecture and human health: A case for effective circadian daylighting metrics. Buildings, 15(3), 315. https://doi.org/10.3390/buildings15030315

Nagare, R., Woo, M., MacNaughton, P., Plitnick, B., Tinianov, B., & Figueiro, M. (2021). Access to daylight at home improves circadian alignment, sleep, and mental health in healthy adults: A crossover study. International Journal of Environmental Research and Public Health, 18(19), 9980. https://doi.org/10.3390/ijerph18199980

Nasrollahi, N., & Shokri, E. (2016). Daylight illuminance in urban environments for visual comfort and energy performance. Renewable and Sustainable Energy Reviews, 66, 861–874. https://doi.org/10.1016/j.rser.2016.08.052

OpenStreetMap. (n.d.). Overview. Retrieved May 3, 2026, from https://www.arcgis.com/home/item.html?id=b834a68d7a484c5fb473d4ba90d35e71

Palusci, O., Monti, P., Cecere, C., Montazeri, H., & Blocken, B. (2022). Impact of morphological parameters on urban ventilation in compact cities: The case of the Tuscolano-Don Bosco district in Rome. Science of the Total Environment, 807, 150490. https://doi.org/10.1016/j.scitotenv.2021.150490

Queiroz, N., Westphal, F. S., & Ruttkay Pereira, F. O. (2020). A performance-based design validation study on EnergyPlus for daylighting analysis. Building and Environment, 183, 107088. https://doi.org/10.1016/j.buildenv.2020.107088

Reinhart, C. F. (2005). A simulation-based review of the ubiquitous window-head-height to daylit zone depth rule-of-thumb.

Reinhart, C. F., & Andersen, M. (2006). Development and validation of a Radiance model for a translucent panel. Energy and Buildings, 38(7), 890–904. https://doi.org/10.1016/j.enbuild.2006.03.006

Robert McNeel & Associates. (n.d.). Rhinoceros 3D. Retrieved May 3, 2026, from https://www.rhino3d.com/en/emea/

Rogers, P., Rasmussen, H., Logadóttir, Á., Hansen Hamre, E., & Vikberg, H. (2025). Towards a wider adoption of EN 17037: A Scandinavian perspective. Lighting Research & Technology, 57(6–7), 649–656. https://doi.org/10.1177/14771535251320664

Rohde, L., Logadóttir, Á., Austmann, J., & Birkisson, R. (2024). Should Danish building regulations legalise basement dwellings?—Consequences for daylight and view out investigated through case studies. E3S Web of Conferences, 562. https://doi.org/10.1051/e3sconf/202456201004

Rostami, E., Nasrollahi, N., & Khodakarami, J. (2024). A comprehensive study of how urban morphological parameters impact the solar potential, energy consumption and daylight autonomy in canyons and buildings. Energy and Buildings, 305, 113904. https://doi.org/10.1016/j.enbuild.2024.113904

Saratsis, E., Dogan, T., & Reinhart, C. F. (2017). Simulation-based daylighting analysis procedure for developing urban zoning rules. Building Research & Information, 45(5), 478–491. https://doi.org/10.1080/09613218.2016.1159850

Sattrup, P. A., & Strømann-Andersen, J. (2013). Building typologies in northern European cities: Daylight, solar access, and building energy use. Journal of Architectural and Planning Research, 30(1), 56–76.

Seto, K. C., Golden, J. S., Alberti, M., & Turner, B. L. (2017). Sustainability in an urbanizing planet. Proceedings of the National Academy of Sciences, 114(34), 8935–8938. https://doi.org/10.1073/pnas.1606037114

Sokol, N., & Martyniuk-Peczek, J. (2016). The review of selected challenges for incorporation of daylight assessment methods into urban planning in Poland. Procedia Engineering, 161, 2191–2197. https://doi.org/10.1016/j.proeng.2016.08.814

Strømann-Andersen, J., & Sattrup, P. A. (2011). The urban canyon and building energy use: Urban density versus daylight and passive solar gains. Energy and Buildings, 43(8), 2011–2020. https://doi.org/10.1016/j.enbuild.2011.04.007

Veitch, J. A., Christoffersen, J., & Galasiu, A. D. (2012, October 1). Daylight and view through residential windows: Effects on well-being. LD+A Magazine.

Volf, C., Bueno, B., Edwards, P., Hobday, R., Mäder, S., Matusiak, B. S., Wulff, K., Osterhaus, W., Manoli, G., Della Giustina, C., Joshi, J., Kämpf, J. H., Vega, K., & Kueffer, C. (2024). Why daylight should be a priority for urban planning. Journal of Urban Management, 13(2), 175–182. https://doi.org/10.1016/j.jum.2024.02.002

Voll, H., Thalfeldt, M., De Luca, F., Kurnitski, J., & Olesk, T. (2016). Urban planning principles of nearly zero-energy residential buildings in Estonia. Management of Environmental Quality: An International Journal, 27(6), 634–648. https://doi.org/10.1108/MEQ-05-2015-0101

Zhu, J., Feng, J., Lu, J., Chen, Y., Li, W., Lian, P., & Zhao, X. (2023). A review of the influence of courtyard geometry and orientation on microclimate. Building and Environment, 236, 110269. https://doi.org/10.1016/j.buildenv.2023.110269

Appendices

Table 14: Heatmap showing cumulative density of annual direct solar hours (h/m^2) across each city.

City:		**Lund**				**Stockholm**				**Luleå**			
Street Width	**No. of floor in Building**	**0°**	**30°**	**60°**	**90°**	**0°**	**30°**	**60°**	**90°**	**0°**	**30°**	**60°**	**90°**
7.5	**3**	101.2	99.9	99.8	101.4	99.7	98.3	97.9	99.9	97.0	95.8	95.6	97.1
	6	73.0	71.2	71.2	73.3	71.0	69.2	69.2	71.2	67.3	66.5	66.3	67.7
	9	56.5	55.4	54.9	56.9	54.4	53.0	53.5	54.9	51.3	50.5	50.4	51.7
	12	45.9	45.0	44.8	46.3	43.9	43.0	43.3	44.5	41.3	40.7	40.7	41.8
10	**3**	104.9	103.9	103.7	105.0	103.2	102.5	102.1	103.5	100.9	100.0	99.8	101.0
	6	77.8	75.8	76.1	78.0	75.6	74.1	73.7	76.0	71.8	70.8	70.7	72.0
	9	61.1	59.6	59.4	61.4	58.9	57.4	57.5	59.4	55.1	54.4	54.5	55.5
	12	50.0	49.1	48.7	50.4	47.9	46.8	47.2	48.5	44.8	44.2	44.3	45.2
15	**3**	109.3	108.6	108.5	109.5	108.0	107.4	107.2	108.3	105.7	105.3	105.0	105.8
	6	84.6	83.0	83.5	84.8	82.6	81.2	81.2	82.9	78.9	78.0	77.8	79.1
	9	68.5	66.5	67.1	68.8	66.2	64.8	64.4	66.6	62.0	61.4	61.2	62.4
	12	57.1	55.6	56.0	57.6	54.9	53.6	53.5	55.4	51.0	50.7	50.5	51.4
20	**3**	112.1	111.6	111.4	112.3	110.9	110.5	110.1	111.1	108.8	108.5	108.2	108.9
	6	89.0	88.1	88.5	89.2	87.1	86.4	86.3	87.3	83.7	83.2	83.0	83.9
	9	73.8	72.4	72.7	74.2	71.6	70.5	70.2	72.0	67.4	66.9	66.8	67.8
	12	62.8	61.2	61.7	63.3	60.4	59.5	59.0	61.0	56.3	56.0	55.8	56.7

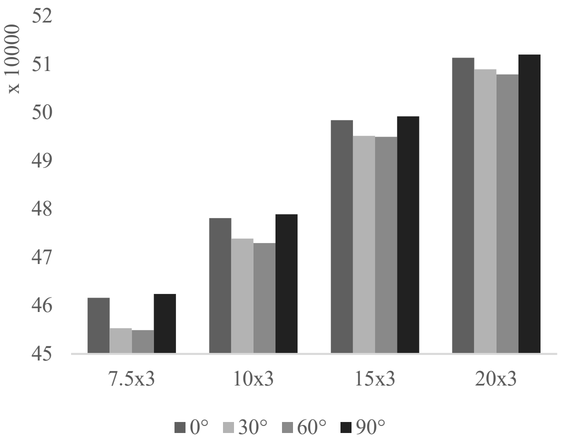


Figure 32: Annual Direct Solar Hour for 3 floor building in Lund.

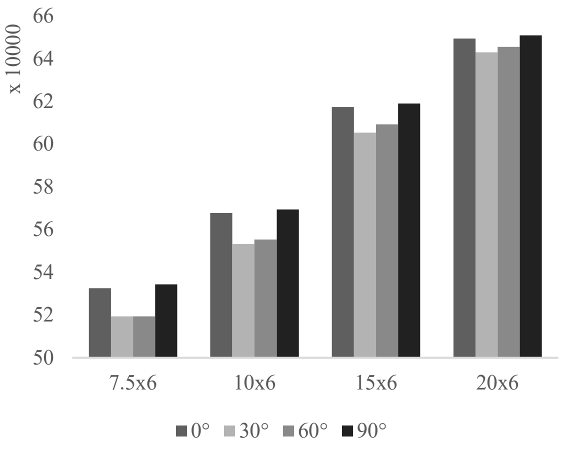


Figure 33: Annual Direct Solar Hour for 6 floor building in Lund.

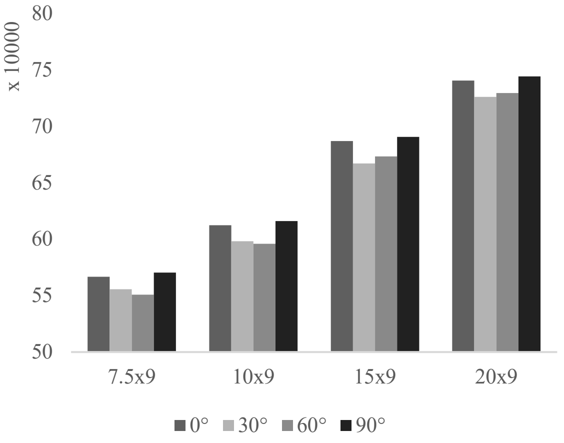


Figure 34: Annual Direct Solar Hour for 9 floor building in Lund.

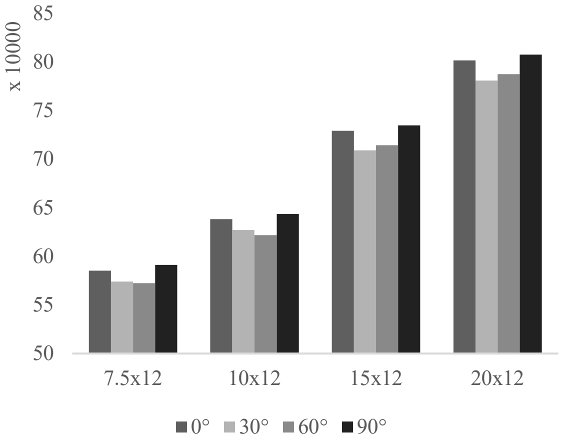


Figure 35: Annual Direct Solar Hour for 12 floor building in Lund.

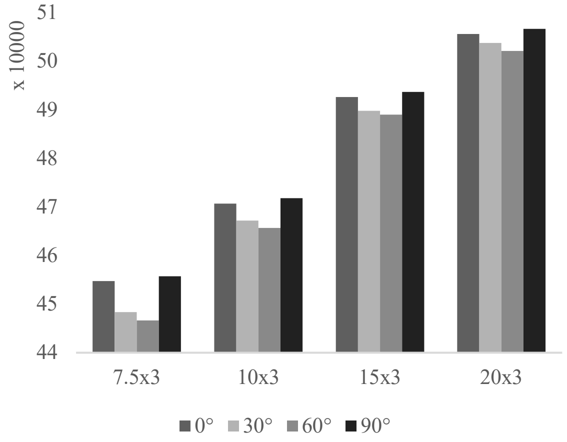


Figure 36:Annual Direct Solar Hour for 3 floor building in Stockholm.

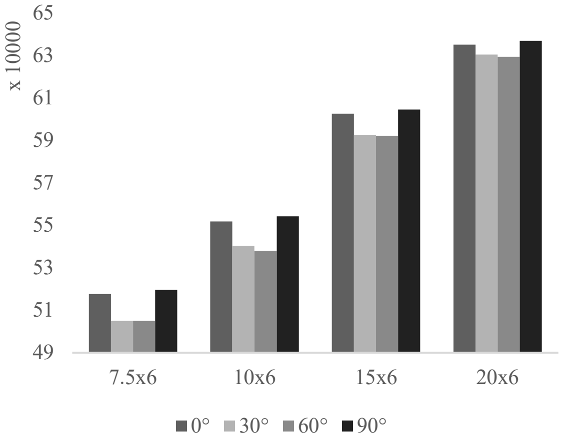


Figure 37:Annual Direct Solar Hour for 6 floor building in Stockholm.

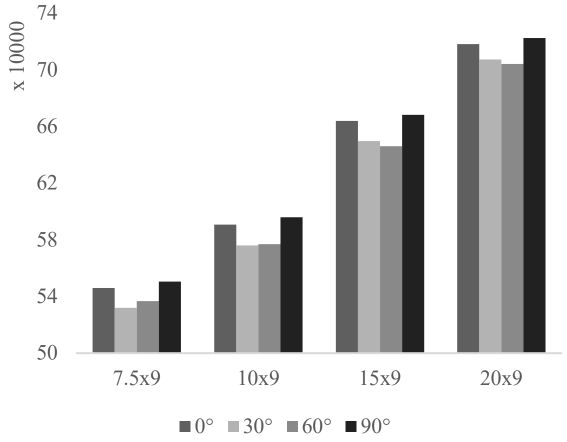


Figure 38:Annual Direct Solar Hour for 9 floor building in Stockholm.

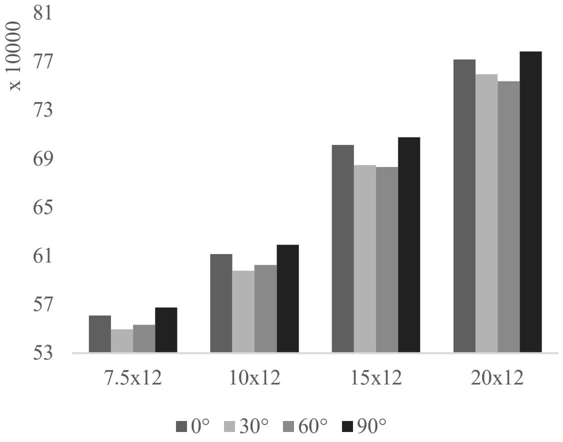


Figure 39:Annual Direct Solar Hour for 12 floor building in Stockholm.

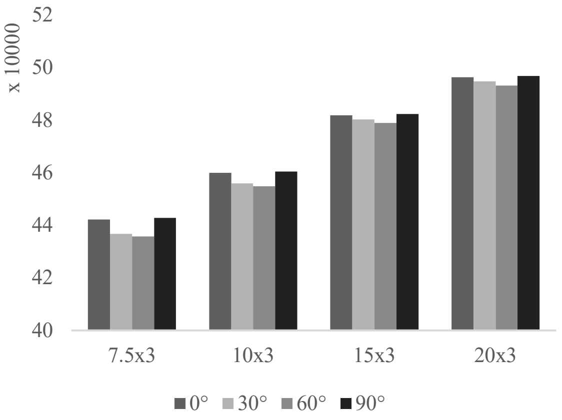


Figure 40:Annual Direct Solar Hour for 3 floor building in Luleå.

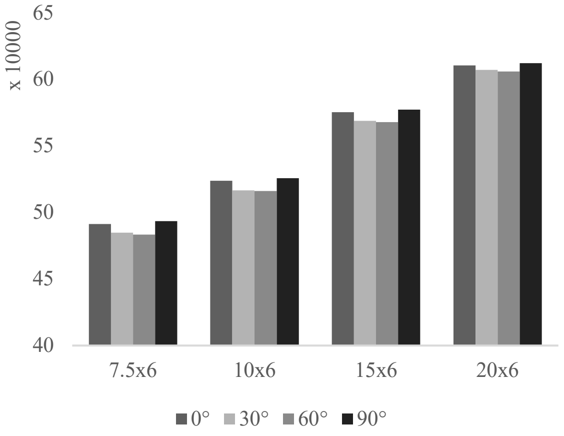


Figure 41:Annual Direct Solar Hour for 6 floor building in Luleå.

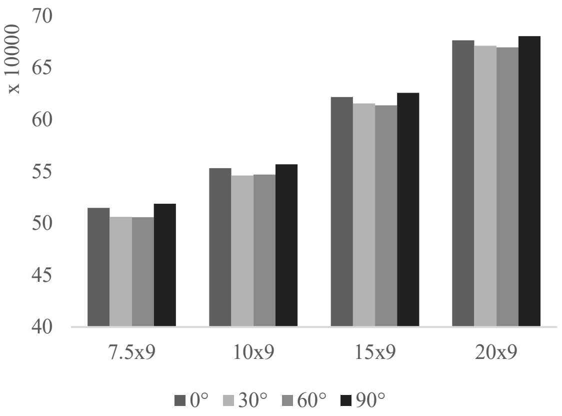


Figure 42:Annual Direct Solar Hour for 9 floor building in Luleå.

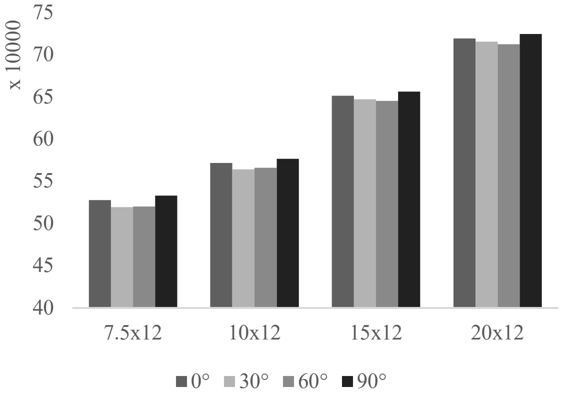


Figure 43:Annual Direct Solar Hour for 12 floor building in Luleå.

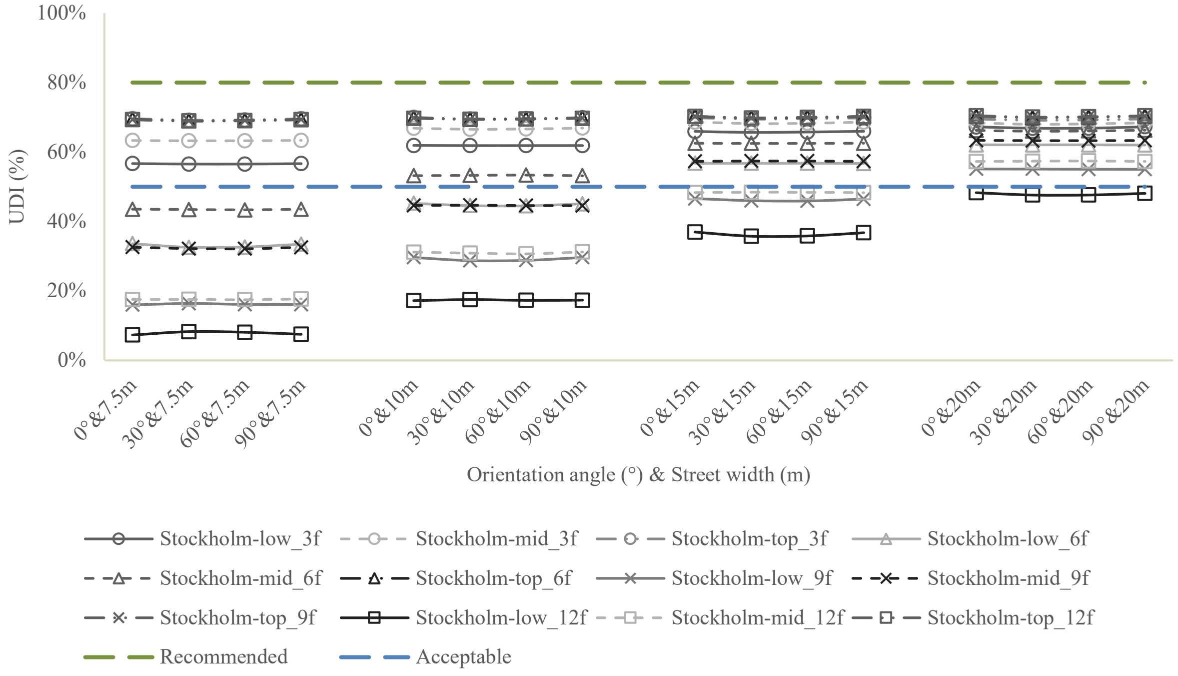


Figure 44:UDI$_a$ of all building type across all orientation scenarios for Stockholm city.

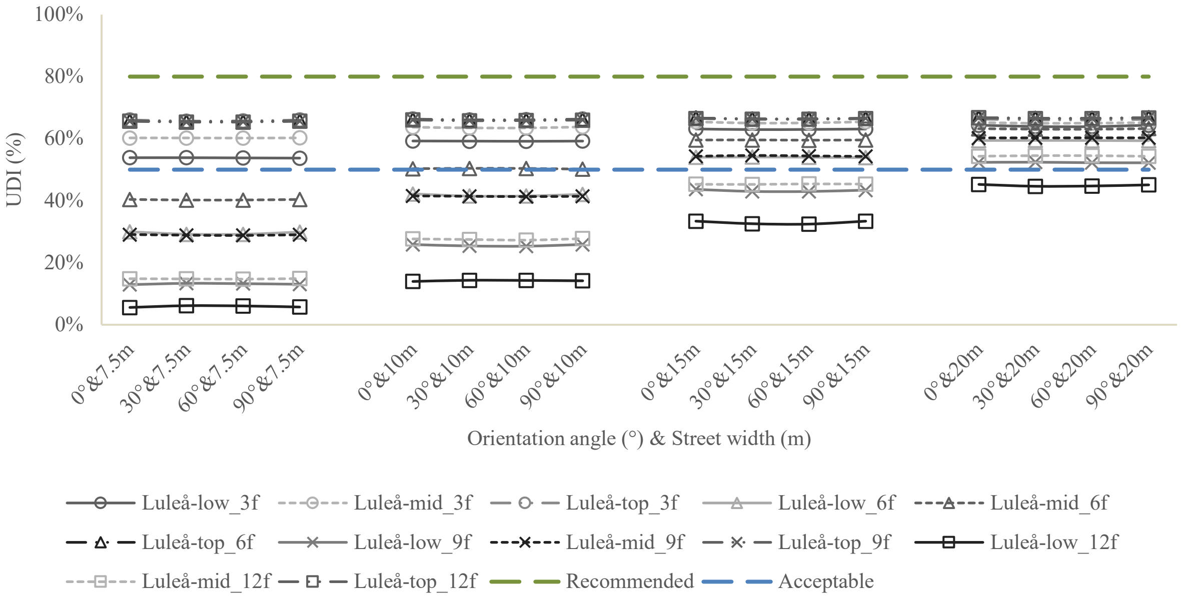


Figure 45:UDI$_a$ of all building type across all orientation scenarios for Luleå city.

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