Solar access indicators for urban planning

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LICENTIATE DISSERTATION

Licentiate dissertation for the degree of Licentiate in Engineering at the Faculty of Engineering at Lund University to be publicly defended on the 10th of February at 10.00 in V:A Hall, Department of Building and Environmental Technology, V-building, John Ericssons väg 1, Lund

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Abstract

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Urban planners receive development directives that often stipulate higher densification of new and existing areas. Presently, some solar access aspects (daylighting and sunlighting) are legislated and evaluated at the late stages of building design, when it is often too late to change basic urban layout features to increase solar access. Thus, the urban planning level appears to be the appropriate design stage for solar access interventions. Having so many urban design objectives to deal with at this planning level, urban planners need simple methods to effectively introduce discussion of solar access into the design process. This thesis aims to contribute to this goal by investigating relevant metrics to identify suitable performance indicators for the purposes of solar access evaluation.

In the first phase, a literature review was conducted to identify existing solar access metrics. The metrics were analysed and arranged into a metric taxonomy. The ways in which assessment metrics are typically formulated were also investigated, which led to structuring of the metric formulation principles. These guidelines may help analysts to select or formulate suitable metrics for specific design evaluations.

In the next phase, the metrics that were identified from the literature review were further examined through correlation studies and statistical methods, including regression models. The study was conducted on neighbourhood models, typical for the Swedish context, including both generic design iterations and case studies. The relationships between metrics and urban density were investigated. The analysis identified four potential metrics (1. VSC, 2. SVF, 3. ASH_F, 4. RD_G) which can help assess solar access at the urban planning phase. They adhere to four design objectives for solar access, recognised as: 1) daylighting indoors, 2) daylighting outdoors, 3) sunlighting indoors, and 4) sunlighting outdoors. These metrics are well-correlated with urban density and with other metrics, yet remain relatively simple.

Finally, two assessment methods that use and apply the identified performance indicators were suggested. Both models require the analyst to input the urban density and choose a target metric. Then, using the metric datasets created in this thesis, the assessment models return either 1) urban design proposals for a given development plot or 2) expected value ranges for a given metric to position the proposed design in reference to the previously simulated cases. The first method leaves less creative space for the planners, while the second method gives only reference values for estimation of the potential to improve a design.

Future work should aim to focus on establishing metric thresholds, i.e., performance benchmarks, as this would further develop workflows for solar access evaluations. Evidence-based research is required to establish recommended solar access levels for the complex network of wellbeing and energy objectives.

Key words: solar access, urban planning, performance indicator, daylighting, sunlighting, neighbourhood, metric taxonomy, urban density

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Acknowledgements

This thesis came to life with support from the Swedish Energy Agency, whom I want to thank for entrusting us with this research. I hope that the results will contribute to the practice of developing sustainable and healthy neighbourhoods.

I would like to express my gratitude to my supervisors Maria Wall, Jouri Kanters, and Niko Gentile for guiding me on this academic journey. I am looking forward to continuing this path with you. I am fortunate to have your support and mentorship. Thank you for all the knowledge you passed on to me.

Big thanks to the research community involved in IEA SHC Task 63 for inspiring discussions and many valuable insights. I hope we will continue to share our experiences.

To my family and friends, I am eternally grateful for your infinite supply of uplifting thoughts and encouraging words. Especially big loving thanks to my partner, whose kindness, support, and companionship mean everything to me.

List of publications

Appended publications

The publications of this licentiate thesis are listed below. All papers were peer-reviewed and published with open access.

Paper I: Czachura, A.; Kanters, J.; Gentile, N.; Wall, M. Solar Performance Metrics in Urban Planning: A Review and Taxonomy. Buildings 2022, 12, doi:10.3390/buildings12040393.

Paper II: Czachura, A.; Gentile, N.; Kanters, J.; Wall, M. Selection of Weather Files and Their Importance for Building Performance Simulations in the Light of Climate Change and Urban Heat Islands. In Proceedings of the ISES Solar World Congress 2021, pp. 1218-1227, 2022, doi:10.18086/swc.2021.46.02

Paper III: Czachura, A.; Gentile, N.; Kanters, J.; Wall, M. Identifying Potential Indicators of Neighbourhood Solar Access in Urban Planning. Buildings. 2022, 12, doi:10.3390/buildings12101575.

The author's contribution to the appended publications

Paper I: The author conducted the review, analysed the data, and wrote the paper.

Paper II: The author designed the study, carried out the analysis, and wrote the paper.

Paper III: The author designed the study, carried out simulations, analysed the data, and wrote the paper.

Other publications by the author in the field

Czachura, A.; Davidsson, H. Integrated Daylight and Energy Evaluation of Passive Solar Shadings in a Nordic Climate. In Proceedings of the ISES EuroSun 2020 Conference; July 19 2021; pp. 32–40.

Baker, N.; Belmonte Monteiro, R.; Boccalatte, A.; Bouty, K.; Brozovsky, J.; Caliot, C.; Campamà Pizarro, R.; Compagnon, R.; Czachura, A.; Desthieux, G.; et al. Identification of Existing Tools and Workflows for Solar Neighborhood Planning. IEA SHC Task 63 - Solar Neighbourhood Planning 2022.

Data availability

The data produced in this licentiate thesis as part of Paper III was published with open access in the Swedish National Data Service with the reference number SND-ID: 2022-137.

Terminology

This section explains some of the key terms used throughout this thesis. Figures 1 and 2 visualise some of these concepts.

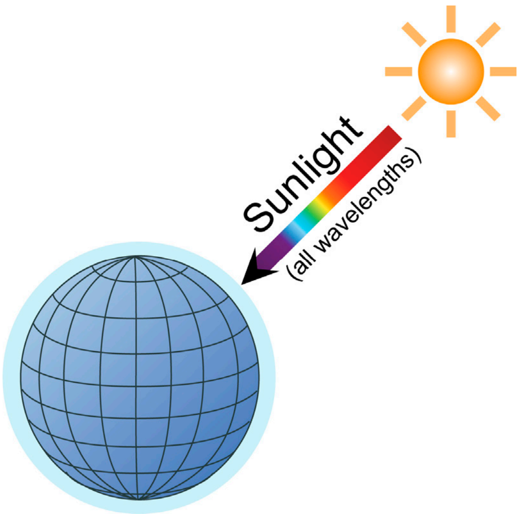

Figure 1
Sunlight is a generic term describing radiation in all spectra that comes from the sun.

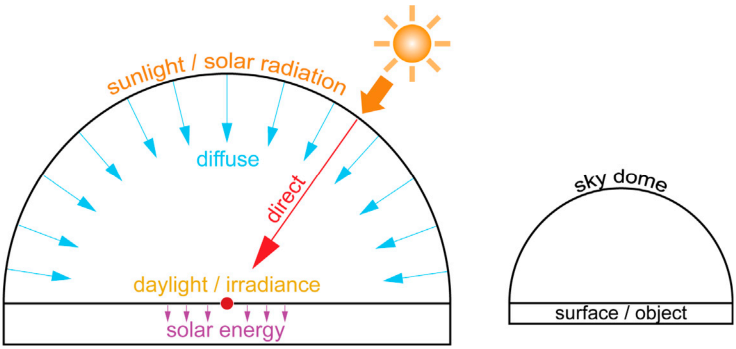

Figure 2
Diagram visualising some of the applied solar concepts and terms.

Sunlight – radiation that comes from the sun, along the entire solar electromagnetic wavelength spectrum (Figure 1).

Sunlighting – design-driven provision of solar access by direct sunlight. The term refers to the connectedness of direct solar rays with the target surfaces of the environment and is typically computed via geometrical analysis using solar vectors (directions of direct solar rays). Sunlighting is thus often expressed by duration of sunlight on a surface, rather than its intensity. No distinction is made between different light spectra. The term "sunlighting" is used in daylighting research to distinguish the provision of the direct sunlight component from the total measured daylight (P. Littlefair, 2001). "Sunlighting" has also been referred to as direct solar access (de Luca & Dogan, 2019). Building Research Establishment (BRE) guide "Site layout and planning for daylight and sunlight" uses "sunlighting" to indicate indoor and outdoor direct solar access (P. J. Littlefair et al., 2022). In the European Standard (EN 17037), the sunlighting objective is defined as "exposure to sunlight" (SSI & CEN, 2021). Some regulations for sunlighting of indoor spaces exist and vary locally (de Luca & Dogan, 2019).

Solar radiation – electromagnetic wavelengths from the sun, with the emphasis on the radiant flux (power). This is a technical term used to refer to the power of radiation coming from the sun. After solar radiation reaches the atmosphere, it splits into a diffuse and a direct component of solar radiation (Figure 2). When solar radiation hits a surface or an object, the value that expresses solar power per area is solar irradiance.

Daylight – a photometric term for the visible portion of radiation from sunlight, i.e., eye sensitivity-weighted radiation in the interval 380-740 nm.

Daylighting – a strategy to use daylight for illuminating e.g. an indoor space. For example, a window is a daylighting component. There are two methods for predicting the level of daylighting in a space: 1) static daylight modelling and 2) dynamic daylight modelling (also known as climate-based daylight modelling). The former uses a diffuse cloudy sky model (without direct sun), while the latter is typically computed with an annual simulation using hourly-based sky models connected to local weather data. Current Swedish and European daylighting regulations require compliance with a static daylight metric (Daylight Factor) (Boverket, 2011; SSI & CEN, 2021). Therefore, in this thesis, daylighting is mainly understood as provision of daylight from a diffuse cloudy sky, irrespective of the sun's position in the sky.

Solar access – a general concept that describes the amount and distribution of sunlight in living environments. This is a general term that defines the connectedness of sun and sky to the environment and its target surfaces.

Solar energy – energy from the sun received by objects on Earth (Figure 2). Depending on how this energy is used, there are passive and active solar energy strategies. Passive techniques usually imply a simple utilisation of solar energy without mechanical systems, whereas active techniques involve the use of mechanised systems (e.g., photovoltaics).

Neighbourhood – in this thesis, defined as a small residential urban area that is not intersected by large high-speed roads, hosting a cluster of buildings.

1. Introduction

1.1. Background

The European building sector is responsible for 40 % of Europe's energy use and 38 % of greenhouse gas emissions (European Commission Department of Energy, 2020). Energy efficiency, healthy environments, and renewable energy sources represent future targets of European development that are highly relevant for the urban planning and building industries (European Commission, 2019). With 75 % of Europe's population living in urban areas (World Bank, 2022), cities will play a major role in accomplishing sustainability goals.

Solar radiation is a valuable energy source that has the potential to decarbonise future cities (Victoria et al., 2021). Solar energy can be harvested directly in cities through the application of active solar energy systems. These may consist of solar thermal collectors to provide hot water or photovoltaic systems to supply electricity directly to buildings and to the power grid. Solar energy is Europe's fastest-growing renewable energy source (Eurostat, 2022). Yet with an average of 37 % of electricity coming from renewables and solar making up only 14 % of renewable sources (Eurostat, 2022), there is a need to implement more solar energy systems and integrate them into urban spaces.

Sunlight contributes to the sustainability of the built environment even through its passive use. First, direct sunlight on buildings and their openings provides internal heat gains and therefore has a significant influence on the building's operational energy use and thermal balance. In heating-dominated climates, direct sunlight through the windows has a positive effect on the building's energy use in winter as it can provide valuable and free energy as passive solar heating. However, in the summer, even in colder climates, sunlight might become a liability, as it adds unwanted heat into buildings and causes overheating (Czachura & Davidsson, 2021), which in turn creates a need for mechanical cooling systems. Second, energy use for electrical lighting in buildings may be reduced by ensuring ample daylight indoors.

Alongside the energy implications of sunlight in cities, there are also important wellbeing-related aspects that should not be neglected. Solar energy affects thermal comfort, both indoors and outdoors. The right amount of daylight improves productivity, but too much light can cause glare issues and visual discomfort. There are also important health advantages to direct contact with sunlight such as improved mood (Rosenthal et al., 1984), better immune response (Holick, 2004), and reduced exposure to microbes (Fahimipour et al., 2018).

Purposely planned solar access to urban areas ensures good solar radiation levels for people, vegetation, building interiors, and strategic surfaces (Figure 3). However, too much sunlight in cities can sometimes lead to accumulation of heat and, if there is insufficient heat dissipation and an abundance of heat-absorbing materials, the urban heat island effect may be activated. Heatwaves are linked with increased mortality (D'Ippoliti et al., 2010), and thus resilience in cities includes preparedness and mitigation regarding extreme temperature events at the level of city planning.

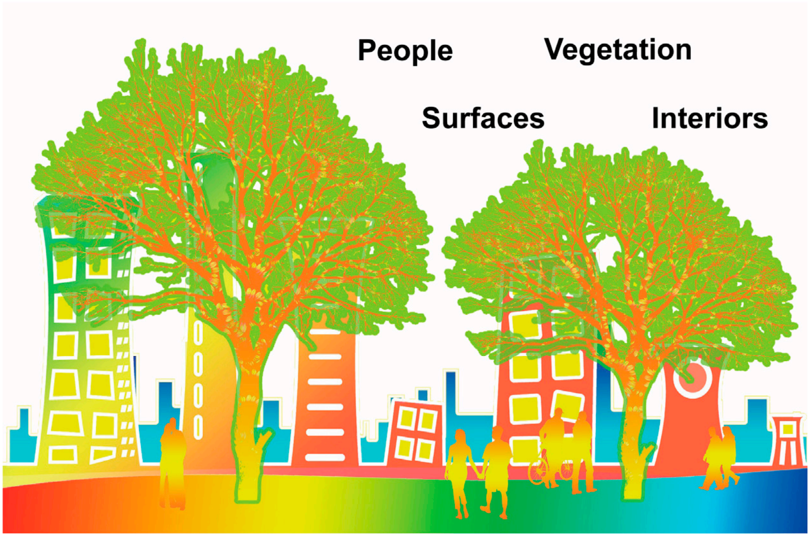

Figure 3
Solar access in cities should ensure sustainable sunlight distribution for people, vegetation, indoor environments, and outdoor surface applications, e.g., PV.

Sunlight boosts another aspect of resilient and climate-neutral cities: vegetation, including local food production. Cities have great potential to produce food at the source (Ljubojević, 2021). An added benefit of increased greenery coverage in cities is reduction of heat island effects (Dimoudi & Nikolopoulou, 2003). Plants have specific light requirements, and thus strategies aimed at effective use of urban surfaces for vegetation growth require prior sunlight assessments at the planning level.

Solar access to urban areas is affected by both natural and man-made obstructions. Landscape features, greenery, and built structures shape the distribution of sunlight into the city fabric. In areas of higher urban density, self-shading and mutual shading of buildings occurs. The amount of solar access allowed into outdoor areas and onto building façade (and further into the interiors) is largely defined at the urban planning level, as building masses are drafted at this stage. For future sustainable cities, it is critical to plan neighbourhoods and relative building masses in neighbourhoods in such a way that appropriate solar access can be guaranteed in the final built environment.

1.2. Theoretical framework

Solar access is considered a broad and general term covering various aspects of sunlight penetration and solar distribution in the urban fabric. It may quantify, using relevant indicators, the level of sky or solar path connectedness to specific target areas of the environment. It may also represent specific levels of solar irradiance on the target surfaces, where certain performance design objectives are applied. Solar access can be expressed in various ways, for instance using measures of daylight, direct sunlight, or by total amounts of solar radiation.

In this thesis, energy and wellbeing are considered the principal objectives of the provision of solar access. Figure 4 presents a map of solar access objectives along with specific performance goals connected to these objectives.

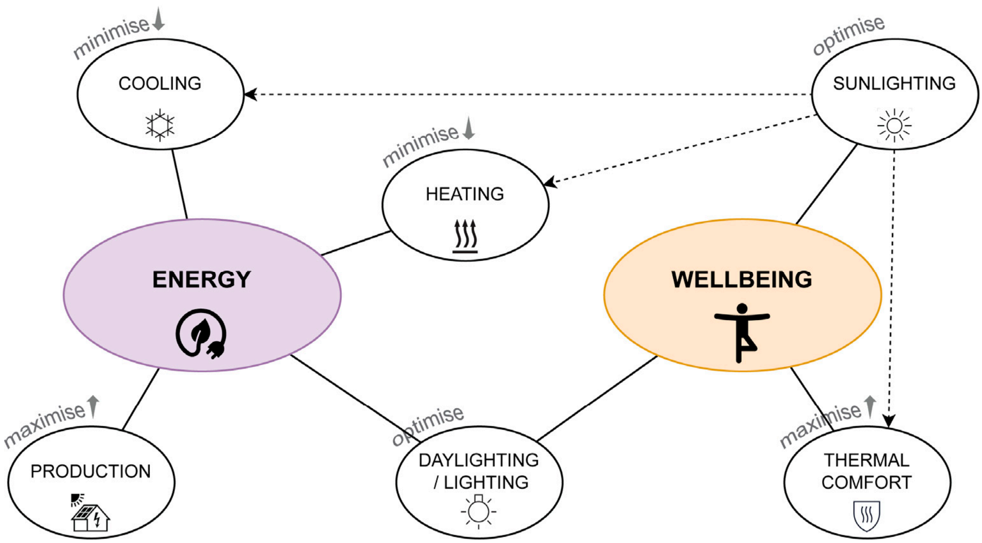

Figure 4
Two main objectives for provision of solar access in urban areas: energy and wellbeing. The items around the main objectives constitute design goals for ensuring good building performance.

In terms of current European legislation, sunlighting is a design goal associated mainly with objectives related to wellbeing (SSI & CEN, 2021). Yet naturally, direct sunlight will impact the thermal balance in the sunlit environment, as indicated in Figure 4. Some local regulations for sunlighting of indoor spaces exist, presenting different evaluation models and performance targets (de Luca & Dogan, 2019). In the European Standard (EN 17037), the recommended sunlighting levels are specified for a point located on the window surface, pertaining to sunlighting of the indoor space (SSI & CEN, 2021).

Solar access needs to be optimised because it brings both positive and negative effects on the quality and performance of urban spaces and buildings. Sunlighting and daylighting are clear examples of design goals that require optimisation (Figure 4), since too much sunlight and/or daylight can have a negative impact on performance. For example, winter solar gains reduce heating demands, but summer solar gains increase cooling demands. Visual and thermal comfort are also compromised by excessive sunlighting and daylighting.

1.3. Problem statement

Cities are growing, and as urbanisation intensifies (World Bank, 2022), densification of existing neighbourhoods and expansion to non-urban land is observed (Angel et al., 2021). City planning must accommodate for a large influx of people in the coming decades (Angel et al., 2021; Mattson et al., 2015). It is projected that by 2050, urban inhabitants will amount to two thirds of the global population (United Nations, 2019). One of the political intentions behind the densification of cities and taller developments instead of expanding the city borders is to protect agricultural land (Seto et al., 2011). Yet, the densification trend has a negative impact on solar access in cities (Bournas & Dubois, 2019), reducing the amount of sunlight and daylight in living environments.

Solar access is an important aspect of urban design. However, from the urban planning perspective, it is one of many complex design issues involving, e.g., wind, transportation, safety, noise, and pollution (Grandjean & Gilgen, 1976). Thus, planning for solar access requires simple methods that are matched to the primitive stage of building design. The urban planning phase begins the building design process by introducing rough building masses at a low level of detail (LoD). Yet, design decisions made at this stage have important implications for solar access. The geometrical constraints of an urban plan determine how much sunlight will be allowed into cities (both indoor and outdoor spaces) and how it will be distributed. The amount of solar access defined by man-made obstructions is virtually unalterable until the end of the service life of buildings and/or neighbourhoods.

Presently, there is no legislative framework for measuring and reporting the solar access quality of urban plans. However, there are legal requirements for the amount of daylight in buildings, which are implemented at the later stages of building design when façade details and internal layouts are established. Europe's example of this legislation is EN 17037 (SSI & CEN, 2021), which regulates daylighting provision using either the Daylight Factor (DF) metric or a more advanced climate-based approach. For sunlighting of building interiors, there is no hard legislation in Europe, and different approaches to measuring sunlighting levels are applied in different countries (de Luca & Dogan, 2019). Europe's EN 17037 sunlighting recommendation suggests a minimum level (duration) of direct sunlight access (cloudless conditions) reaching a window surface, calculated on a reference date (SSI & CEN, 2021).

The requirements for indoor daylight and sunlight levels may be hard to meet at the later stages of building design because of insufficient provision of solar access (Šprah & Košir, 2020). Urban planners may neglect to include solar access in design considerations due to lack of time or competence, or inability to alter planning decisions (e.g., urban density) made at the governance level (Kanters & Wall, 2018; Mattson et al., 2015). Simple evaluation procedures are needed to optimise solar access in densified cities, yet suitable methods are lacking (Nault et al., 2015). Consequently, highly obstructed solar access must be compensated for in the later stage of building planning by large window sizes (Chokhachian et al., 2020), which may lead to glare and overheating issues (Czachura & Davidsson, 2021) as well as higher heating demands in wintertime. In order to meet the daylighting standard required in the late design stages, Swedish urban planners who took part in a workshop expressed the need to prioritise provision of solar access for daylighting in their plans (Kanters et al., 2021).

Metrics that are prescribed in legislation and used to assess the performance of advanced building designs are often ill-suited for early design evaluations at the urban planning level because of their high complexity. These metrics require sophisticated inputs that are unknown in the early design stages. Details such as window arrangement and properties, façade elements (e.g., balconies), roof shapes, and internal layouts are necessary for calculating certain typical performance metrics, for instance pertaining to daylighting or energy use, but in the urban planning phase, many of the inputs have not yet been determined. This design stage requires simple metrics that can be obtained quickly and easily, as urban planning practices are multidisciplinary and cover a wide range of issues. There has been no consensus yet on the recommended metrics for solar evaluation of urban plans, and the metrics that are currently used for solar access assessments have not been supported by enough evidence to sustain their application as performance indicators.

1.4. Aims and purpose

The general purpose of the research carried out in this thesis is to develop early design assessment methods and planning routines for improved solar access in neighbourhoods. The research seeks to identify suitable metrics that can be used in prediction and assessment models. The goal is to establish performance indicators that can facilitate planning for good solar access (Figure 5).

The context for the presented research is the Northern European and in particular the Swedish built environment and urban planning practice. However, the implications of this research could be relevant for other locations with similar solar access conditions.

The specific goals of the thesis are to:

- Systematise existing knowledge about the function, purpose, and formulation of metrics;
- Create a systematic taxonomy of solar performance metrics used for urban and building design assessments;
- Demonstrate metric correlations for increased understanding of their mutual relationships;
- Expand the metric base by adding new metrics as potential candidates for performance indicators;
- Create a database of simulated solar metric values;
- Find simple metrics with high suitability for accurately assessing solar access in urban planning;
- Suggest preliminary methods of applying metric datasets in planning for solar access; and,
- Check the viability of weather data for calculating metrics, particularly solar weather parameters.

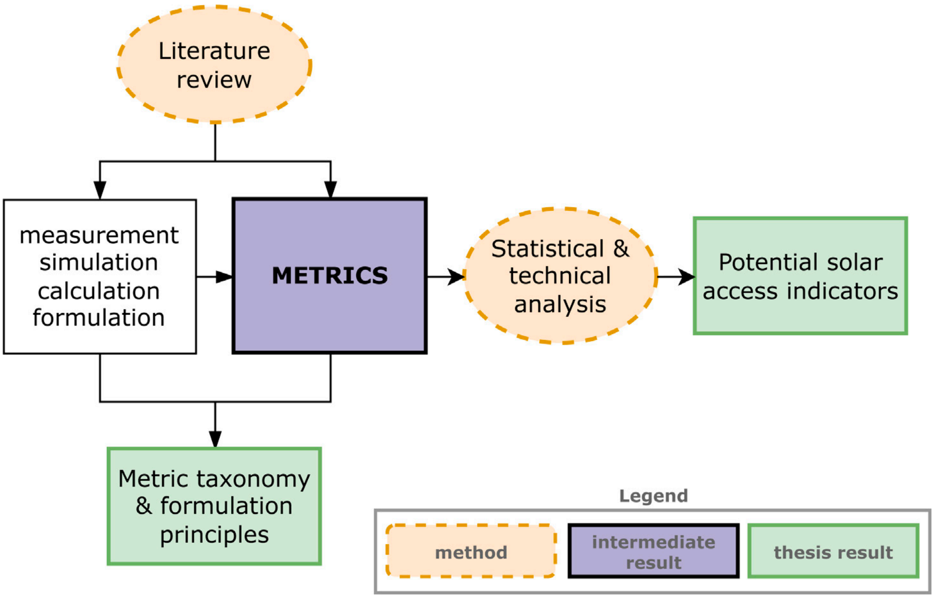

Figure 5
Simplified workflow of methods and findings of the thesis.

1.5. Limitations

This thesis focussed on identifying solar access metrics specifically targeted for the urban planning stage. Therefore, complex late-stage metrics were not considered.

Furthermore, the selection of neighbourhood was limited to homogenous and evenly spaced layouts with continuous building heights. The uniform heights of the buildings in this thesis ensure that the roofs are not obstructed by other buildings. Thus, solar access was measured only on vertical façade surfaces and horizontal ground surfaces, disregarding the solar access on the roofs.

The aspects of solar access in focus in this thesis were limited to wellbeing- and energy-related objectives; other aspects such as effects on microclimate and vegetation growth were not considered.

1.6. Research questions

This thesis aims to answer the following main research question (RQ):

RQ: Which metrics are suitable as performance indicators of solar access in the assessment of urban plans?

There are several other relevant questions that are associated with the main RQ and which this thesis seeks to answer; these are listed below.

Q1: How are metrics developed depending on the purpose of assessment?

Q2: How can metrics related to solar access research be classified based on the complexity of data inputs?

Q3: Are the legislated solar access metrics well-correlated?

Q4: Can simpler metrics substitute more complex ones in measuring solar access?

Q5: How can solar access metrics be applied in solar neighbourhood assessments at the urban planning level?

2. Methods

An overview of the methods applied in this thesis is presented in Figure 6. Methods are grouped by the scope of the three different papers, which are appended to this thesis. The flow of the applied methods leads to study outcomes that aim to answer the main and subsidiary research questions, as marked with circles in Figure 6.

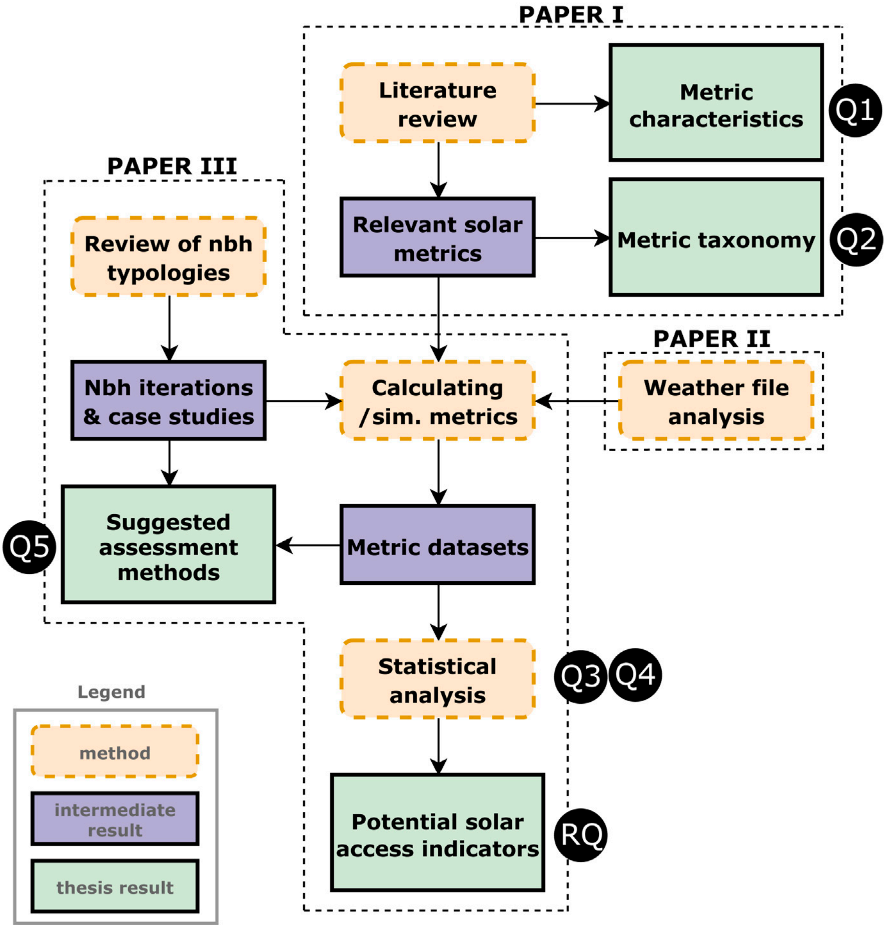

Figure 6
Flowchart of the methods and results of the thesis, including links to the research questions (black circles). 'Neighbourhood' is abbreviated as 'Nbh'.

The initial phase consisted of a literature review (Paper I), which provided the relevant solar metrics for subsequent steps. In Paper II, an analysis of simulation weather data and climate parameters was conducted to validate weather file selection for solar assessments. This was a pre-study to determine the sensitivity of solar weather parameters and to inform the choice of appropriate weather data source for the next study. Paper III examined the relevant solar metrics that were obtained by simulating neighbourhood models. To prepare the models for the metric analysis, a review of neighbourhood typologies in the Swedish context was conducted. Consequently, the neighbourhood models, the relevant metrics, and the suitable weather file were used to calculate metric datasets using validated building simulation software. The generated metric datasets were further analysed using statistical methods to identify potential solar access indicators.

The approach used for the review in Paper I was integrative (Snyder, 2019). The search for relevant scientific papers was carried out in the Scopus scientific database (Elsevier, 2020) using three main concept keywords (with synonyms): solar access, metric, and neighbourhood.

Metrics found in the literature were analysed focussing on the following aspects: a) general descriptions and uses of metrics, b) methods of metric formulation, c) methods of metric communication, and d) functions of metrics.

Some metrics that were identified from the literature review as potential performance indicator candidates were applied further in the technical analysis of metrics. Other metrics were developed and formulated specifically for this analysis to broaden the base of metrics in the study.

Two types of neighbourhood models were used for the analysis of metrics included in Paper III: iteration-based designs and case studies. The case study set of neighbourhood models was used to validate the findings from the iteration datasets. Three typologies were selected for the neighbourhood models: courtyard, slab, and tower (Figure 7). These were identified as the most common neighbourhood types in the Swedish context. With varying heights, side dimensions, and building offsets, the dataset of iteration designs consisted of 1,290 unique design cases. Including the different rotation (orientation) angles applied to the geometries, the modelling set consisted of 3,035 cases. The neighbourhood designs were homogeneous, which means that each was generated using a uniform building type of equal size and shape, which was then replicated into a 5 x 5 neighbourhood grid. The modelling level of detail (LoD) was kept at LoD1, which means that the roofs were modelled flat, and there were no façade details assigned.

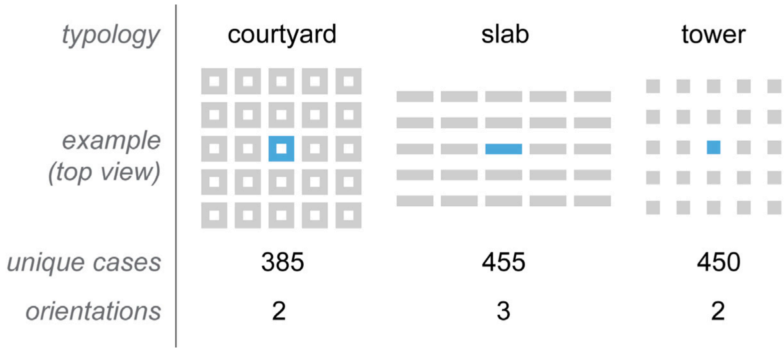

Figure 7
The studied neighbourhood iteration cases.

The neighbourhood case studies were selected from Malmö city districts. They were nearly homogeneous and of one of the same three types as the iteration-based neighbourhoods (Figure 8). Modelling resolution was also kept at LoD1. The neighbourhood models did not include any urban landscape elements other than the buildings. Selection criteria for identifying relevant neighbourhood case studies were established. These criteria also helped define the boundaries of any given neighbourhood.

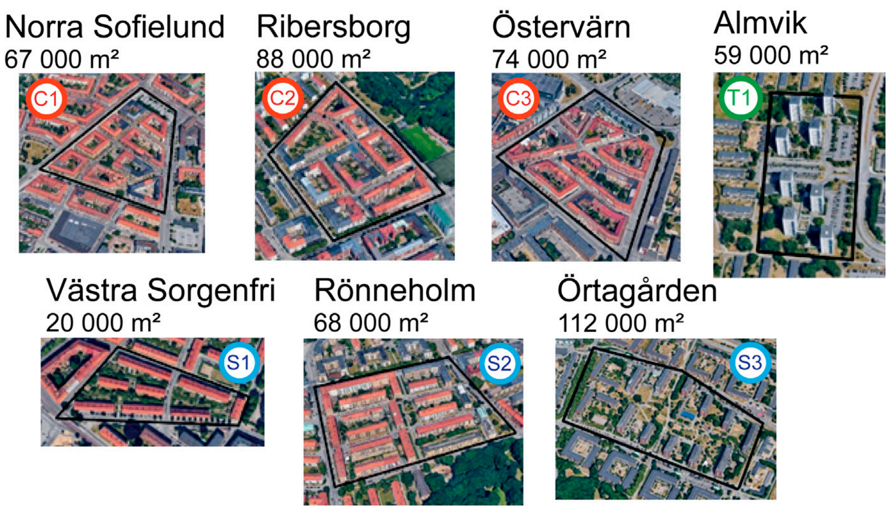

Figure 8
Malmö neighbourhood case studies used in the metric analysis. C – courtyard, S – slab, T – tower.

Some notable metrics that were analysed in this thesis are listed and described in Table 1. The metrics were in part obtained from the literature, while some were generated for the purpose of this study to fill evident gaps between the available metric types. Metrics were calculated for the whole neighbourhood or for a subject area. Metrics referring to the outdoor solar access were calculated for the ground surface, while those reflecting the solar access indoors through apertures were calculated for the façades, as shown in Figure 9. Furthermore, metrics that were calculated for the façades considered either the whole façade as a grid or just a string of points at the approximate level of ground-floor windows (Figure 10).

Table 1
Examples of metrics selected for analysis.

Acronym	Name	Subject	Calculation or simulation method [unit]
FAR	Floor Area Ratio	whole	Ratio of gross floor area to plot area [m²/m²; used as unitless]
VAR	Volume Area Ratio	whole	Ratio of gross building volume to plot area [m³/m²; used as unitless]
SVF	Sky View Factor	ground	Grid-based (1 m), 145 sky patches, cosine-weighted sky dome [%]
VSC	Vertical Sky Component	façade (string)	At 1.4 m height, 1,024 sky patches, CIE overcast sky [%]
RD_G	Reference Day (Sunlight Hours)	ground	Grid-based (1 m), ray intersection, average hours of direct sunshine on 21 March [h]
RD_F	Reference Day (Sunlight Hours)	façade (string)	Grid-based (1 m), ray intersection, average hours of direct sunshine on 21 March [h]
ASH_G	Annual Sunlight Hours	ground	Grid-based (1 m), average direct solar access as fraction of all annual hourly sun vectors [-]
ASH_F	Annual Sunlight Hours	façade (string)	Grid-based (1 m), average direct solar access as fraction of all annual hourly sun vectors [-]
RAD_F	Solar radiation (mean)	façade	Grid-based (1 m), annual solar radiation mean per façade area [kWh/m²]

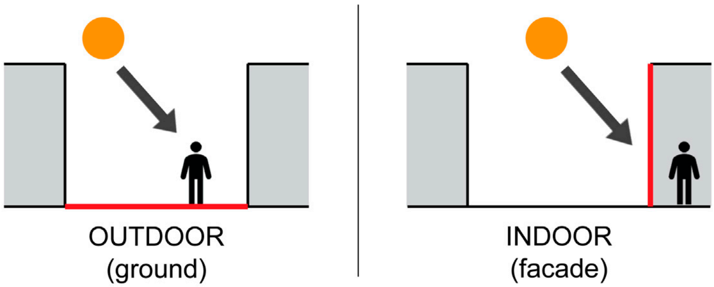

Figure 9
Two types of analysis surfaces (ground—left, façade—right) used to assess the outdoor and indoor environment.

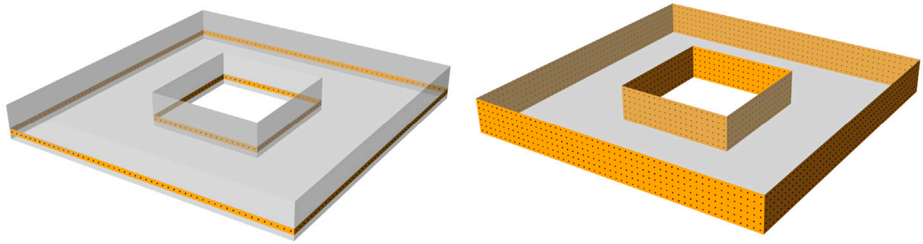

Figure 10
Two types of point grids used in simulation for façade-based metrics. Left: single string of points at 1.4 m height. Right: the whole façade made into a grid of points.

The neighbourhood models were modelled in Rhinoceros 7 (McNeel & Associates, 2021) and Grasshopper (McNeel & Associates, 2022). The metrics were calculated for two locations: Frankfurt and Stockholm, using EnergyPlus weather files (EnergyPlus, 2021), where applicable. Climate and location-based simulations were conducted in Grasshopper using Ladybug tools (Ladybug Tools, 2021). Metric datasets were then analysed using statistical methods, such as regression analysis, data distribution analysis, and correlation analysis. Statistical analyses were conducted in RStudio (RStudio Team, 2021).

3. Results

This section presents the main findings of the thesis, which were also depicted in Figure 6. Sections 3.1 (Metric characteristics) and 3.2 (Metric taxonomy) recap the findings of Paper I. Section 3.3 (Weather file analysis) summarises the results of Paper II. Lastly, sections 3.4 (Potential solar access indicators) and 3.5 (Suggested assessment methods) present the main results of Paper III.

3.1. Metric characteristics

A metric is defined as "a system for measuring something" (Cambridge University Press, 2022). There is a variety of metrics used in solar access studies. The results of the literature review on solar performance metrics specify three key characteristics of metrics, which play an important role in formulating meaningful metrics for performance assessments. These characteristics are metric functions (Figure 11), methods of metric formulation (Figure 12), and methods of metric communication (Figure 13). These characteristics may be used as formulation principles when creating a metric intended for design assessments and performance predictions. Metrics that are formulated in a more systematic way may help practitioners and researchers to achieve better clarity of assessment methods, increased understanding of results, and higher precision of design evaluations. While the focus of the analysis was on solar performance metrics, the metric characteristics (formulation principles) are more general and could also be applied to other engineering fields.

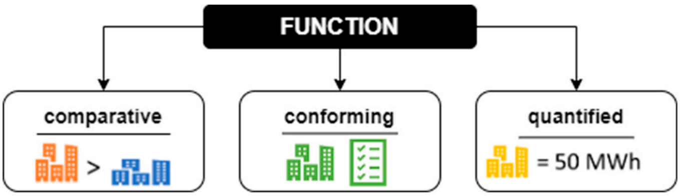

Figure 11
Metric functions were identified as comparative, conforming, or quantified.

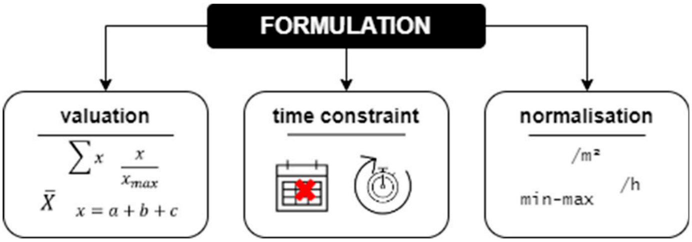

Figure 12
Metric formulation techniques may involve valuation methods, time constraints, and normalisation methods.

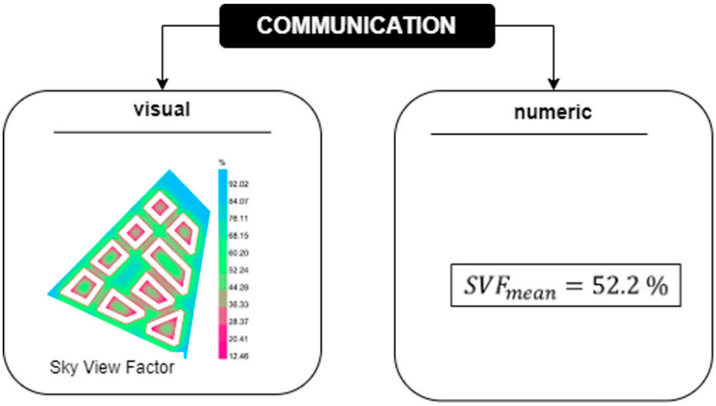

Figure 13
Two main methods of communicating metrics are visual (via graphical displays) and numeric (via numbers). This example shows the Sky View Factor metric calculated and presented graphically: a visual metric (left), and as an average value: a numeric metric (right).

3.2. Metric taxonomy

The metrics identified through the literature review were grouped into metric groups and classes and were placed in a taxonomy of solar building performance metrics (Figure 14). The taxonomy was developed based on the type and complexity of data input needed to obtain a metric. Four metric classes were identified: geometrical (G), latitudinal (L), external climatic (EC), and internal climatic (IC). The classes evolve from the lowest complexity of data input (G-metrics) to the highest complexity input (IC-metrics). Within these classes, there are groups of metrics that further distinguish between different types of metrics based on their features and calculation methods.

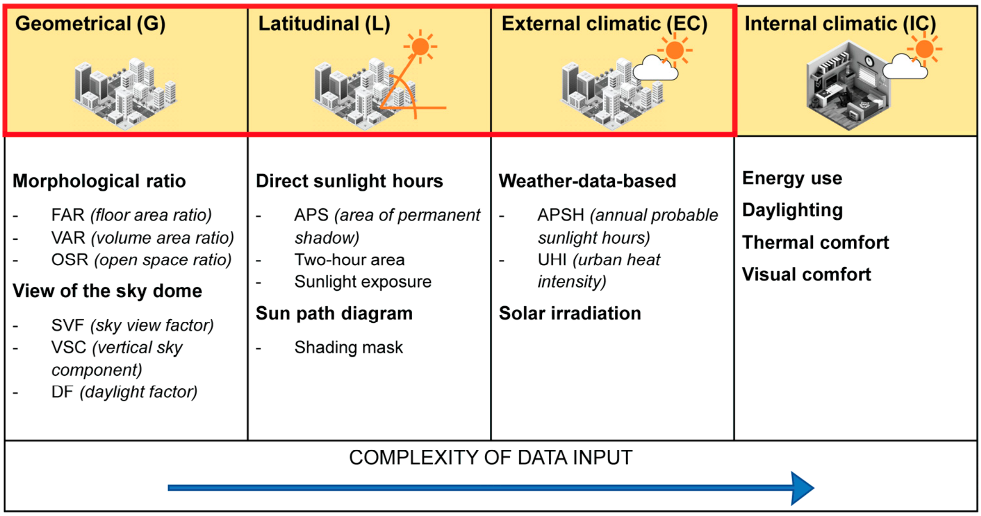

Figure 14
Metric taxonomy presenting metric classes in the top row and metric groups in the middle row, including some examples of metrics (bulleted). The metric classes that were found suitable for early design assessments are highlighted in red.

The types of data input required to calculate a solar performance metric of any given class are presented in Table 2. At the urban planning stage, information about façade and internal design details is not available; therefore, only G-, L-, and EC-metrics appear suitable for solar assessments at the urban planning level.

Table 2
Types of data input required to obtain metrics belonging to the four classes.

Data input	Metric classes			
	G	L	EC	IC
geometrical dimensions	✓	✓	✓	✓
latitude		✓	✓	✓
orientation		✓	✓	✓
insolation (climate)			✓	✓
façade details (incl. window placements)			(✓)	✓
internal layouts and schedules				✓

3.3. Weather file analysis

The analysis indicated that careful selection of weather files for simulations is crucial for hygrothermal parameters but has little impact on solar parameters of the climate. Hygrothermal parameters are influenced by climate change factors and the impact of proximity to urban centres (urban heat island effect). In both scenarios, the study showed that temperatures increase on average. However, with regard to solar parameters, there was no significant statistical difference observed between different weather files. This suggests that there seems not to be a need for special care when selecting weather files for solar access studies. More care should be applied to the selection of weather files for building performance assessments involving hygrothermal aspects.

3.4. Potential solar access indicators

The analysis carried out in Paper III revealed that solar metrics of varying complexity have a high level of correlation to one another, which is demonstrated in Figure 15. It is important to note that simpler metrics (of lower complexity) correlate well with higher complexity metrics. Furthermore, the analysis showed good correlation scores between urban density metrics (FAR, VAR) and other solar access metrics.

		G				L				EC
		FAR	VAR	SVF	VSC	RD_G	RD_F	ASH_G	ASH_F	RAD_F
G	FAR									
	VAR	98								
	SVF	-83	-84							
	VSC	-84	-85	89						
L	RD_G	-78	-79	85	80					
	RD_F	-67	-68	68	72	72				
	ASH_G	-80	-81	86	81	91	70			
	ASH_F	-82	-82	81	85	82	73	85		
EC	RAD_F	-79	-80	80	85	71	67	72	77	

99-86 85-76 75-66 [%]

Figure 15
Correlation scores of selected metric pairs.

Floor Area Ratio (FAR) and Volume Area Ratio (VAR) are two very similar indicators that express urban density. This study found VAR to be a more adequate measure of density for solar performance applications, as it is irrespective of floor height, making it easier to compare studies of different built forms.

Radiation metric (RAD_F) showed high sensitivity to deviations from homogeneity in urban design. Façade shapes, non-right corner angles, and irregular layouts may significantly affect the estimated radiation value. This was demonstrated by a difference between the homogeneous iterated design cases and the case studies, despite having the same LoD. Effectively, the regression lines for case studies did not match the regression lines of the iteration-based design cases for RAD_F. This observation suggests that quantitative assessments of solar radiation in the massing stages are futile. Precise energy potential estimation at this design stage is unachievable because radiation-based metrics are sensitive to late design details and will further become reduced as urban masses shape into more sophisticated forms.

It can be argued that simple metrics are sufficient early indicators of solar radiation potential at the urban scale. High correlation scores were observed between these metrics (Figure 15). Previous studies have demonstrated the potential of SVF as a solar radiation predictor (Chatzipoulka et al., 2018; Chatzipoulka & Nikolopoulou, 2018). Since high estimation precision cannot be achieved and radiation analyses are more complex and time-consuming, simple metrics appear as suitable candidates for early comparative indications of solar radiation potential.

The analysis of metrics led to the identification of four distinct objectives for solar access in urban settings. The objectives are a combination of target environment (indoor or outdoor) and target solar access aspect (daylighting or sunlighting). Generally, at the urban planning level, indoor solar access is assessed at the façade level, while outdoor solar access can be measured at both ground and façade level in case of special solar façade applications. In this thesis, however, the recommendation is that general outdoor solar access for good living environments is assessed on the ground surface.

Based on the analysis of metrics, four suitable early assessment metrics were suggested for each of the solar access objectives (Table 3). These metrics showed good correlation scores and were validated by case studies that closely match the relationship curves of all design cases (Figure 16).

Table 3
Four metrics identified as potential performance indicators of solar access at the urban planning level. Each metric serves a different assessment objective.

	Indoors	**Outdoors**
Daylighting	VSC	SVF
Sunlighting	ASH_F	RD_G

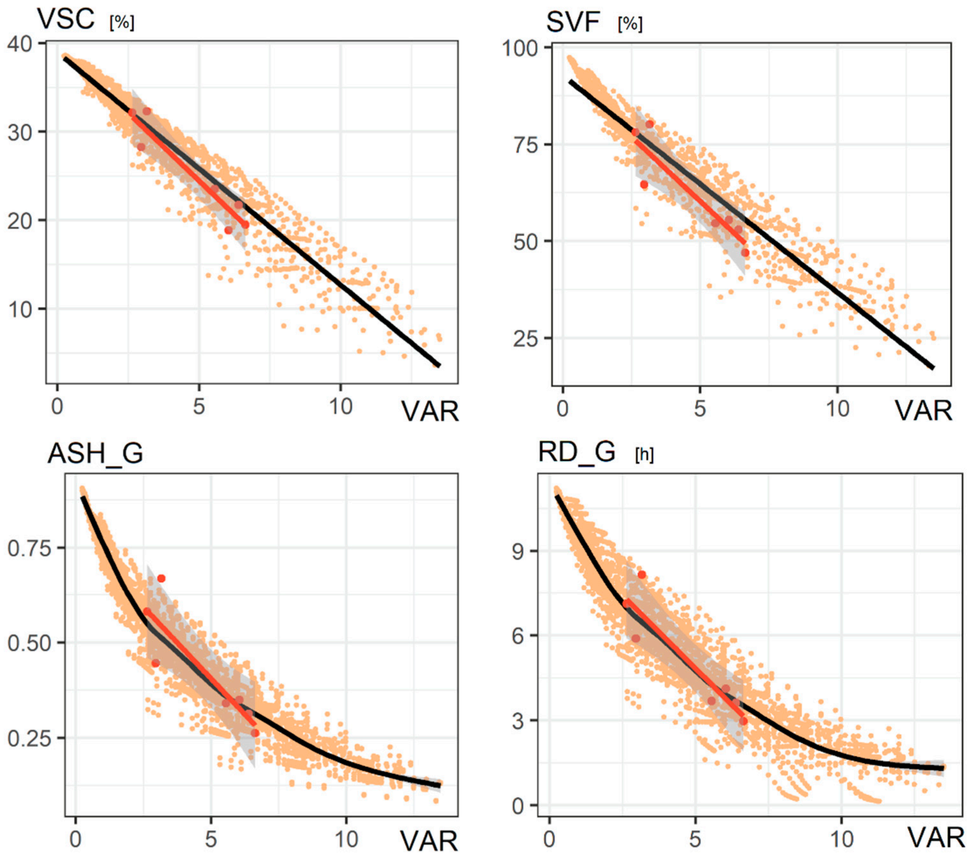

Figure 16
Linear (top) and non-linear (bottom) regression curves showing the relationship of potential solar access indicators to urban density metric, VAR. The black line represents the iteration-based neighbourhood cases, while the red line represents the case studies. The iteration-based regression curves fall within the confidence intervals (grey areas) of the case study regression lines.

3.5. Suggested assessment methods

The urban planning stage of building design lacks many of the inputs necessary for performing detailed performance assessments. As such, this design stage is also driven by political actions and development needs. The prevailing inputs for the early planning phase are the projected number of inhabitants, land size, and urban density.

This analysis suggests two ways in which to apply the validated metric datasets generated in this study. Both methods require the analyst to select a target urban density of the planned development and decide which objective to consider, i.e., which metric to use as performance indicator (see Table 3). In the first suggested method, the analyst applies the urban density value to the performance indicator dataset and may preview the best-performing examples of neighbourhood layouts (Figure 17). This could be further developed into a planning tool that would generate suggestions for urban designs with high solar access. With the alternative method, the analyst may instead look at the reference values for metric ranges based on the simulated neighbourhood cases and use the range as a guideline for assessing their own urban design proposals (Figure 18). The analyst will then know whether their design falls into the high or low range of metric values, in order to identify the room for improvement.

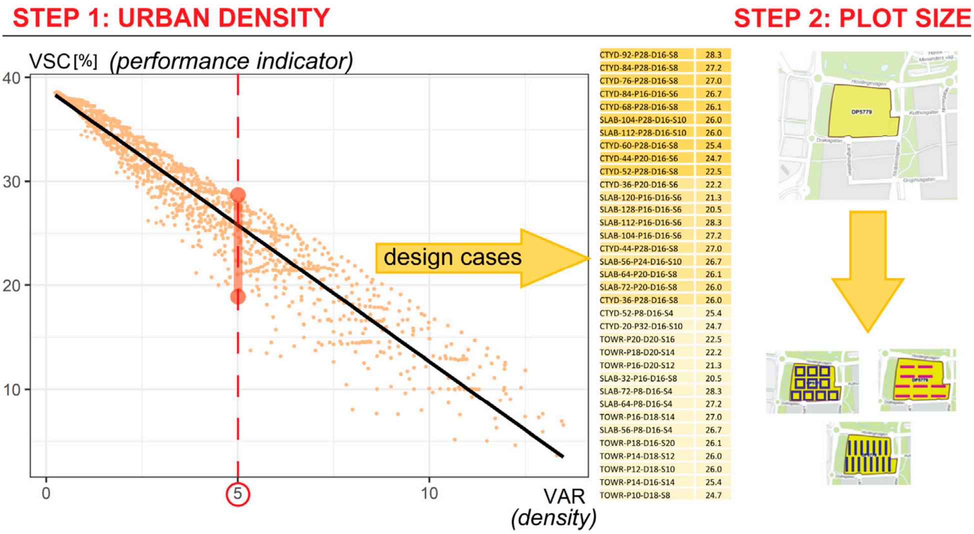

Figure 17
A suggestion for using the metric datasets in solar assessments in urban planning. Assuming target urban density and using the plot as a design input, urban planners may receive suggestions for the best design options.

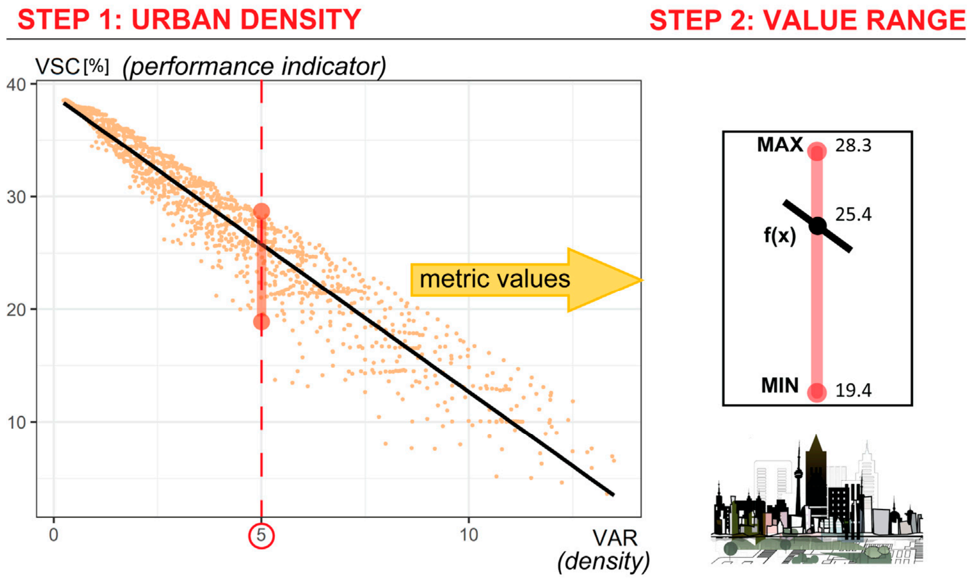

Figure 18
An alternative suggestion for using the metric datasets in solar assessments in urban planning. Assuming target density, urban planners are presented with the expected range of metrics as a reference to be compared with metric results of their own design proposals.

4. Discussion

4.1. Research questions

This section discusses the importance of this thesis work by addressing the research questions stated in the beginning of the thesis.

> **RQ:** Which metrics are suitable as performance indicators of solar access in assessments of urban plans?

The main research question of the thesis work was answered, as suitable metrics were suggested (see Table 3). Each metric is intended to address a specific solar access objective: 1) daylighting indoors – VSC, 2) daylighting outdoors – SVF, 3) sunlighting indoors – ASH_F, and 4) sunlighting outdoors – RD_G. The validity of the methods used for the metric identification was ensured by a) using a large dataset of simulated neighbourhood models, b) statistical comparisons of regression lines of iteration-based models with case studies, and c) checking for high correlation to urban density.

This thesis emphasised that metrics intended for use in early planning assessments must be simple, comparative, and easy to obtain and understand. The resulting metrics (VSC, SVF, ASH_F, RD_G) fulfil these prerequisites.

It should be noted that the suggested metrics are only numeric. In the design process, it may be of value to produce spatial graphical versions of results with coloured surfaces and appropriate legends for visual assessment and detection of critical points. This thesis recommends that the analyst perform initial assessments using the suggested numeric metrics, and potentially in the next steps, produce visual representations of results for further design inspection. All four of the proposed metrics for performance indicators are well-suited for visual grid-based assessments.

Importantly, the next step towards establishing functional performance indicators for solar access studies is to determine thresholds of the suggested metrics. Further research must define the upper and lower benchmarks based on a multitude of factors, including more complex and qualitative aspects such as microclimate, wellbeing, and subjective perception of solar access.

> **Q1:** How are metrics developed depending on the purpose of assessment?

Metric formulation principles, metric functions, and methods of metric communication were defined in this thesis. These outline the basic characteristics of metrics that must be considered when developing a metric for the purpose of measuring something. Further, the purposes of assessments were indicated by metric functions, which may be classified as either comparative, conforming, or quantified.

A metric that is consciously developed to serve its purpose may become a valuable performance indicator. On the contrary, a metric that is poorly developed may be misinterpreted or ill-suited for its intended application. The proposed formulation principles aim to help the analyst to develop useful metrics that would suit the intended function within performance assessments. The formulation principles may also help to interpret existing metrics to establish their purpose and correct applications.

> **Q2:** How can metrics related to solar access research be classified based on the complexity of data inputs?

Solar access metrics were classified into a taxonomy, and four metric classes were identified based on the complexity of data inputs needed for obtaining metrics. The classes consist of 1) geometrical, 2) latitudinal, 3) external climatic, and 4) internal climatic. The input complexity increases for each higher class, as seen in Table 2.

Additionally, metric groups within the four classes were identified. Unlike the classes, the metric groups were not bound by complexity, but rather by the means of obtaining them. Thus, the coverage of groups is open to new additions; there might be more relevant groups of metrics that fall under the defined metric classes.

> **Q3:** Are the legislated solar access metrics well-correlated?

The legislated solar access metrics in the Swedish context currently consist of daylight and exposure-to-sunlight stipulations (SSI & CEN, 2021), which pertain to indoor solar access by daylighting and sunlighting. This thesis looked at the sunlighting metric only, as the daylighting metric relies on internal building features. The sunlighting metric is a threshold-based metric, which means that in order to comply, the calculated metric must score above a certain performance threshold. The sunlighting metric is also calculated for one selected reference day (typically 21 March).

The findings of this thesis suggest that the threshold-based sunlighting stipulation may not perform well as a solar access metric. In general, threshold-based metrics did not correlate well with other metrics nor with density indicators. It is suggested to therefore avoid applying threshold-based metrics in comparative studies involving various design proposals. Thresholds are important in assessments as they communicate levels of performance, but to confidently apply conforming metrics, the selected thresholds must be meticulously verified to prove high correlation with performance.

The results also showed that assessing sunlighting levels on façades is better done with an annual metric (ASH_F) rather than an equinox-based metric (RD_F). The annual metric showed better correlation scores and smoother relationship graphs. The reason for this is that façades are sensitive to orientation because they are directional. On the equinox, the sun moves only on one half of the sky dome, which leaves the north façade orientation with zero-hour potential for direct sunlight.

> **Q4:** Can simpler metrics substitute more complex ones in measuring solar access?

It seems that simpler metrics can not only substitute more complex ones, but they are in fact even more suitable for the early assessment phase where a lot of the building design details are still unknown. Simple metrics, considered to be those of classes G and L, demonstrated good correlation with urban density and with the EC radiation metric.

> **Q5:** How can solar access metrics be applied in solar neighbourhood assessments at the urban planning level?

This thesis suggested two methods of applying the produced metric datasets into assessments of urban plans. The datasets can be used in two ways. The first provides an analyst with ready suggestions for urban designs, which exhibit high levels of solar access (Figure 17). The second would have the analyst assess the solar access potential of bespoke urban designs by comparing the design's metric score with the provided metric ranges for a given urban density (Figure 18).

The main difference between the two suggested assessment methods is the level of design autonomy of the analyst. The first method tends towards automation of the design process, suggesting possible urban layout solutions for a specific density and high solar access. The second method simply gives the analyst a value reference to assess solar access in the given urban design and to discern the potential for improvement.

Both of the suggested methods should be revised once metric thresholds are established. Setting solar access level benchmarks will improve solar assessment methods. The thresholds should instate boundaries for the recommended minimum and maximum solar access levels.

4.2. Limitations

This thesis outlined the scope of solar access objectives and goals (see Figure 4), but some relevant goals were neglected. For instance, the thesis did not consider urban heat island issues. There were two main reasons for this: a) microclimate simulations are complex and sensitive to unique and detailed designs, and this thesis assumed simplified models; and b) vegetation plays a major role in the heat balance of cities, but in this thesis, it was a conscious choice to disregard the surface types of the ground plane. However, the SVF metric has previously been associated with urban heat island mitigation (Theeuwes et al., 2017); thus, a small link to urban heat studies exists in this thesis, but it is not a main concern. Similarly, the thesis did not focus on solar access for food production purposes. However, the ASH_G metric could be useful for ensuring good direct solar access for vegetation growth, and future studies should investigate this potential.

There were further limitations in the selection of metrics:

- The analysed metrics were all numeric without considering visual metrics.
- The metrics were calculated in such a way as to express a single value for any given neighbourhood case, using the arithmetic average. This was to ensure comparability of metrics and design cases.
- Metrics were correlated to each other and to urban density, but a correlation analysis with the late design (IC) metrics was not performed due to high level of uncertainty and the need for many assumptions. This should, however, be further examined.
- The selection of metrics was based on the literature. Potentially, further metrics could be relevant for solar access and could be tested. The metric datasets from this thesis were published with open access online (Czachura & Lund University, 2022), so anyone can reuse this data and further contribute to this research.

Furthermore, there were limitations to the modelling of the neighbourhood cases:

- The LoD was set to a low value, which provides a very simplified building form, without realistic shapes, design details, or other elements of the city fabric, such as vegetation and infrastructure.
- Some assumptions about the neighbourhood cases such as the homogeneity, typology limitation, and size constraints might have restricted the ranges and variances of metric databases and might have influenced the observed relationships. More urban forms, including hybrid examples, should be studied.

5. Conclusions

This thesis studied solar metrics with the aim of increasing knowledge and improving assessment routines of solar access evaluations of neighbourhoods at the urban planning level. The main findings encompassed:

- Metric characteristics and formulation principles;
- Solar access metric taxonomy;
- Potential performance indicators of solar access at urban planning level; and,
- Suggested methods of solar access assessment at the early urban planning stage.

The overall metric characteristics and solar metric taxonomy provide a structured foundation for the process of selection, creation, and procurement of assessment metrics. A systematic way of selecting or creating metrics for specific assessment purposes, using the metric formulation principles, can facilitate design evaluations and aid decision-making. Correct metric formulation can improve the metric's design-descriptive power, which in turn leads to highly informed design decisions with strong emphasis on performance. Furthermore, assisted by the metric taxonomy, navigating solar access metrics and their different classes may prove easier and more transparent.

The thesis identified four solar access indicators (metrics (VSC, SVF, ASH_F, and RD_G) for assessments at the urban planning stage. This represents an important contribution towards establishing reliable solar assessment workflows and validating the associated methods. This thesis assessed the suitability of a range of commonly used metrics and proposed potential performance indicators. Each indicator was aimed at one of four different solar access objectives, which are a combination of the solar access goal (daylighting or sunlighting) with the target environment (indoor or outdoor). Matching validated indicators with specific solar access objectives should improve the usability of early-stage solar access evaluations and increase confidence in applying assessment metrics.

The metric datasets resulting from this thesis can be used as a practical reference and analytical support in solar access assessments at the urban planning level. Two methods of applying the proposed solar access indicators were suggested. Both the indicators and the methods are of suitably low complexity for the intended design intervention phase. The analyst may choose between a method of higher or lower degree of intervention. These methods are the result of initial attempts to develop assessment workflows and should be further improved. For this purpose, performance thresholds for the proposed indicators should be established.

6. Future work

The present work focussed on the identification of metrics as suitable performance indicators for urban planning assessments of neighbourhood solar access.

As a continuation of this research, future work aims to establish performance thresholds for the proposed solar access metrics (Figure 19). The work intends to apply quantitative and qualitative methods to establish evidence for solar access levels and associate performance with specific metric values. Metric thresholds must be further examined to assess their predictive power. The end goal would be to establish validated performance indicators and develop reliable assessment methods for early-stage solar access evaluations.

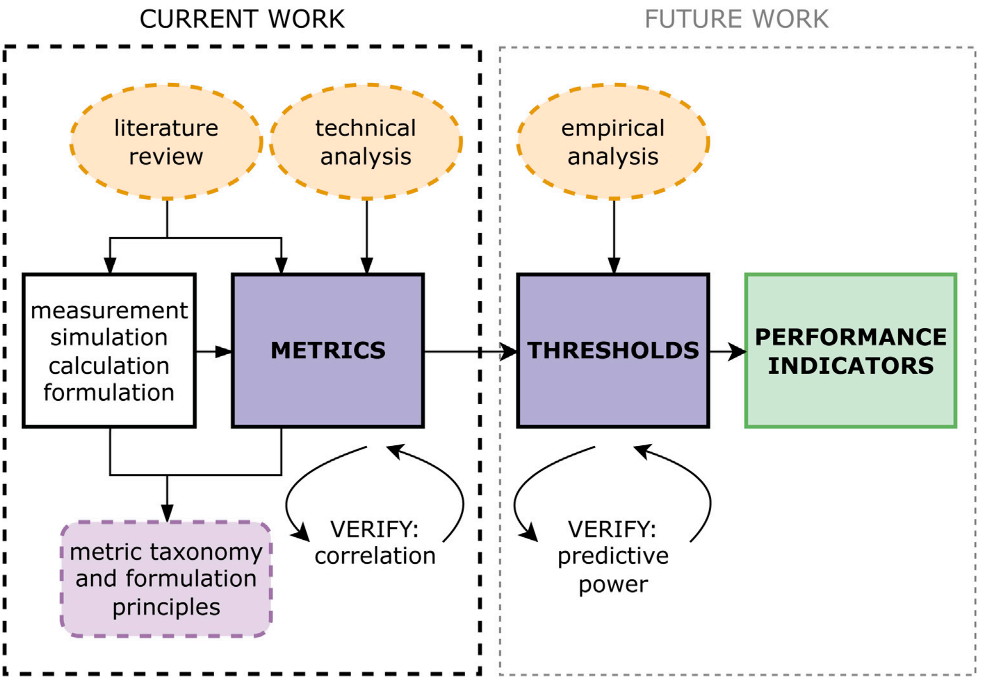

Figure 19
Simplified workflow diagram outlining current and future work of the present research.

Currently, out of the four solar access objectives presented here, only two – daylighting indoors and sunlighting indoors – are legislated. While daylighting standards are supported with extensive research, the sunlighting recommendations need more empirical evidence. Future work should focus on establishing performance thresholds for sunlighting indoors and outdoors and for daylighting outdoors. The performance criteria should be translated into design benchmarks for the solar access indicators in the urban planning assessment workflows.

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