DAYLIGHT PREDICTION BASED ON THE VSC - DF RELATION

A guideline for daylight in urban planning

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Master thesis in Energy-efficient and Environmental Buildings
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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

In 2017, 255 of Sweden's 290 municipalities reported a shortage of residential housing (Boverket, 2017). The answer is to build more. Due to urbanization pressure, concerns for saving valuable agricultural land, growing national and EU demands on energy-efficiency, there is an increasing number of new and dense urban developments. Daylight issues seem to have been of little concern in development of many of these new detailed plans, and daylight in buildings is often studied much too late into the project.

The aim of this master thesis was to seek through computer simulations for a simple method to assess daylight availability in residential housing at an early design phase. It is based on a presumed relationship between the median Daylight Factor and the in Sweden rather unfamiliar Vertical Sky Component (VSC).

Both the VSC and median Daylight Factor where evaluated for a simple room geometry located on the ground floor of five courtyard building typologies. Our aim was to obtain general threshold values of VSC to ensure that the Swedish national requirements of good access to direct daylight can be met. Additionally, the impact of both Glazing-to-Floor Ratio and the room depth on the base-case O-shaped typology was assessed and a guideline was formed.

A target VSC was found to be 29% to assure DFmed 1% indoors with conventional window and room design. Following the guideline, in the façade areas where VSC is below 15% it would be difficult to reach the target DFmed.

The performance of the proposed method was evaluated against common threshold values and rules-of-thumb. It was found that predictions from the established principles were often too optimistic.

Acknowledgements

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A special thanks to all the exceptional professionals at FOJAB arkitekter for the great and relevant discussions we had to help shaping the output of the study. And last, but not least, we would like to recognize the whole FOJAB arkitekter for facilitating us!

We are also grateful for the valuable feedback from Paul Rogers, one of daylight experts in Sweden, and his recognition of our thesis.

Contribution

The initial idea of Helena Bülow-Hübe and Magdalena Stefanowicz was discussed, adopted and developed in close collaboration with them. Through equal contribution of authors the scope and methodology of the work was further established. Both Ance and Nevila as a joint team stand behind the results presented in this thesis.

Nomenclature

DF	*Daylight factor*	[%]
E	*Illuminance*	[lux]
ERC	*Externally reflected component*	[lux]
IRC	*Internally reflected component*	[lux]
GFR	*Glazing-to-floor ratio*	[-]
GWR	*Glazing-to-wall ratio*	[-]
SC	*Sky component*	[lux]
VDF	*Vertical daylight factor*	[%]
VSC	*Vertical sky component*	[%]
WWR	*Window-to-wall ratio*	[-]

Abbreviations

BRE	*Building Research Establishment*
BBR	*Boverket building regulations by The Swedish National Board of Housing*
SS	*Swedish Standard*
BREEAM	*Building Research Establishment Environmental Assessment Method*
CBDM	*Climate Based Daylight Metrics*
LEED	*Leadership in Energy and Environmental Design*
SBUF	*Swedish building branch development fond*

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1 Introduction

1.1 Background

The world has witnessed a dramatic increase of its population, especially in recent centuries. According to the United Nations (2017), there are approximately 6 billion more inhabitants nowadays compared to 1900 and the world population is projected to reach 9.8 billion by 2050. This exponential population growth has led to a rapid urbanization process, resulting in population concentration in urban settlements. Apart from social, economic and environmental effects, one of the inevitable consequences has been the utmost plot exploitation, resulting in denser cities and more high-rise buildings, and space availability is constantly diminishing.

This considerable population growth and consequently increased number of buildings have implications on future energy needs, as the building sector is responsible for 40% of energy consumption and 36% of CO_2 emissions in the EU according to the European Commission database. As a response, the Energy Performance of Buildings Directive (EPBD) and Energy Efficiency Directive were proposed, with the purpose of mitigating building's impact on energy use and the environment. When trying to address the energy issue, daylight performance can be negatively implicated, as one of the most obvious and cost-effective measures is to reduce the window area. Additionally, the pressure from the urbanization process has increased building density or the floor space index. Many new developments are much denser than we have been used to historically. An obvious consequence when courtyards become smaller or when buildings are built taller than previously is that the access to insolation and direct skylight decreases.

Many researchers have studied the importance of daylight and its social and health benefits but also the potential to reduce the energy demand, as more daylight means less dependency on electrical lighting. As Dubois et. al (2017) implies, better daylight utilization could potentially yield a 25% reduction of electricity use for lighting. Thus, achieving a balance between energy and daylight interest becomes more essential, and more attention to this question must be given in the early stages of design.

According to a debate article by (Alenius & Lundgren, 2016), daylight was historically guaranteed by city planning rules which controlled building height and street width like in the legislation introduced in 1874. These kinds of rules governed city development until the 1960s. It was in the 1960 building regulations, when a daylight requirement was mentioned for the first time (Rogers, et al., 2015). Later, the circumstances related to the first oil crisis in 1973 directed the focus on energy requirements and the window size got significantly restricted. In that period, the metric Daylight Factor (point), measured at half depth of the room one meter from the darkest wall, was introduced and an attempt to explain how it can be calculated followed in 1987 (Löfberg). Afterwards, a simplified method based on glazing area was developed as a standard and included as part of the Swedish building code, but it is associated with a lot of application limitations.

Even though the industry's interest in daylight has not always been the priority, it has recently gained greater attention, especially in the last 10 years. This is much related to the establishment of the Swedish building certification system "Miljöbyggnad", which has become quite popular. In this system, there is a mandatory daylight requirement and daylight compliance is quite rigorously controlled during the certification process.

From this retrospective, what can be noted is that all the focus regarding daylight has been on the DF metric and on the building level. As Rogers (2017) states, in Sweden there is no daylight regulation in the early planning phase. This often causes problems in the following phases, especially with the current housing crisis and the recent construction boom. Therefore, it is important to introduce a simple conceptual metric, such as the Vertical Sky Component (VSC), with a two-folded purpose. On one hand it can be used by urban planners or architects when detailed development plans are compiled and on the other hand it can be a tool for the architects in the conceptual phase when the volume is defined, but before the window or room distribution is decided.

This study is an attempt to develop a set of guidelines which would facilitate the process of daylight estimation during the early design phase. This can potentially save considerable time and resources while being able to grasp the possibility of daylight level indoors just by evaluating the vertical façade daylight levels. Moreover, most of the current research is focused on atrium or urban canyon typologies and on the relation between daylight factor and geometry dimensions, proportions and surfaces properties. Therefore is was considered valuable to investigate various courtyard typologies, especially their inner corners.

1.2 Objectives and research questions

The main aim of this study was to develop a generalized tool and find benchmark values that can allow urban planners and architects to evaluate daylight potential at the early stages of building design. The thesis explores the relationship between the Vertical Sky Component and indoor Daylight Factor with the purpose to possibly identify those areas where improvements and redesigning is needed in order to reach the required amount of indoor illumination.

Research questions:

1) What is the relation between the DF and the VSC?
2) Does the building typology have an impact on the VSC-DF relation?
3) Could a VSC threshold be found and used to evaluate the potential of achieving the required DF indoors?

Some other specific objectives are listed below:

- Assess the impact of higher ground reflection than standard 0.2
- Investigate the relation between DF and VSC when different glazing-to-floor area ratios are applied
- Evaluate how different room depth contributes to the VSC – DF relationship

1.3 Scope and limitations

It was necessary to set some boundaries while conducting this study, in order to complete the task within the given timeframe. The focus was on residential building types derived from the closed courtyard typology. A simple rectangular room geometry situated on the ground floor, facing the inner side of the courtyard was simulated.

Further limitations listed below were:

- The building shape was simplified and fixed standard room geometry was used in order to achieve shorter computational time
- No overhead obstructions such as balconies or shading devices were included
- Theoretical models did not consider adjacent vegetation or other obstructions apart from the building itself
- No furniture was assumed indoors.

1.4 Thesis Outline

This study is organized in five chapters, where Chapter 1 introduces the background of the topic, identifies the problem and motivation for the study and addresses the research objectives and limitations.

Chapter 2 covers a brief theoretical background study on variables and methods used and further discusses current design guidelines, standards and related scientific research articles.

Chapter 3 presents the method of the theoretical study by introducing building typologies and design parameters examined.

Chapter 4 presents the main results of all the options considered and identifies the outline of a relation between the metrics observed.

In the Chapter 5 the results are discussed by reviewing the chosen method, validation and sensitivity of the results. It also elaborates in detail on the limitations of the conducted study and analyses how they affected the results.

Additionally, Chapter 6 through two exemplary scenarios previews the developed guideline application based on known VSC and DF-VSC relations observed from the Phase 2 results.

2 Theoretical framework

This section contains an overview of the theoretical background necessary to understand the contextual background of the study. In the following chapters, information on the main variables, daylight assessment methods and outline of the current building standards, thresholds and research advancement is presented.

2.1 Description of variables

This part presents the general background information and definitions of the metrics and influencing factors discovered in the study.

2.1.1 Daylight Factor

In architecture, the illumination originating from the sun in form of daylight and sunlight is highly varying and therefore a complicated element to describe. The quantity of daylight in a room depends on the brightness outside and therefore often expressed as a Daylight Factor (DF).

Fundamentally, the DF expresses the ratio between the interior illuminance from daylight to the exterior illuminance. It can be regarded as the sum of three components that express three possible paths along which light can reach a point inside a room through windows. It is the (SC) Sky Component (the illuminance received directly from the part of the visible sky) supplemented with (ERC) Externally Reflected Component (the illuminance received from reflective exterior surfaces), and (IRC) Internally Reflected Component (the illuminance reflected from interior surfaces), as shown in *Figure 1 A*.

$$E_i = SC + ERC + IRC \tag{1}$$

The DF is expressed as the ratio between illuminance in a room and the simultaneous illuminance from the sky on an unobstructed horizontal surface:

$$DF = \frac{E_i}{E_h} \cdot 100\% \tag{2}$$

Where DF is the Daylight Factor in percentage, E_i is the daylight illuminance at a point on the workplane indoors [lx], E_h is the daylight illuminance on an unobstructed horizontal plane outdoors measured in lux [lx], see *Figure 1 B.*

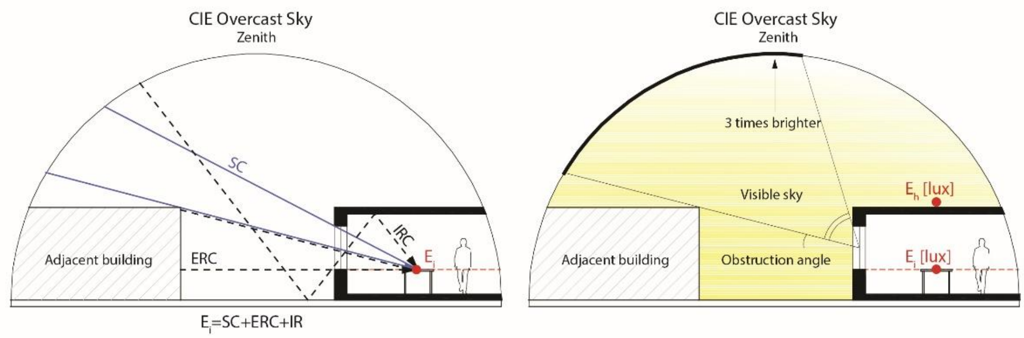


Figure 1 A - DF as sum of three components; B – DF as a ratio of external and internal illuminance.

Traditionally, the daylight factor is calculated for a standardized luminance distribution of the sky, i.e. the CIE standard overcast sky, see chap 2.1.4. From the definition of this sky follows that the daylight factor in a room is independent of window orientation, as the luminance distribution is rotationally symmetric.

2.1.2 Vertical Daylight Factor

Both the SC and ERC can be expressed as the Vertical Daylight Factor (VDF), measured at a point on the vertical external surface, usually in the middle of each main window.

VDF is defined by Li, Cheung, Cheung & Lam (2009) as the ratio of the total amount of daylight illuminance falling onto a vertical surface to the horizontal illuminance from a complete hemisphere of sky simultaneously under CIE standard overcast sky.

$$VDF = \frac{E_s + E_r + E_g}{E_h} \cdot 100\% \tag{3}$$

Where E_s – direct light from the sky [lux]; E_r – reflected light from surroundings [lux]; E_g – reflected light from ground [lux] and E_h – the horizontal illuminance of an unobstructed sky.

Under normal circumstances, the VDF largely depends on the reflectance of the ground, surrounding buildings and other obstructions. However, the exact values of the surfaces in an urban context might not yet be defined, especially at early planning phases.

2.1.3 Vertical Sky Component

The Building Research Establishment (Littlefair, 2011) has defined the Vertical Sky Component (VSC) as the ratio between that part of illuminance that is received directly from a CIE standard overcast sky at a point on a set vertical plane, and the horizontal illuminance from a complete hemisphere of sky. The maximum value for a CIE overcast sky is 39.6% (Littlefair, 1998).

$$VSC = \frac{E_s}{E_h} \cdot 100\% \tag{4}$$

The VSC is proposed to be used instead of VDF to merely indicate the daylight access. The amount of daylight is mainly determined by the sky luminance, and therefore the VSC calculation is simplified by excluding ERC and the impact of reflected daylight from the ground and the surroundings (Li, et al., 2009).

Fundamentally, the VSC is closely related to the VDF, and could be simulated considering only one ambient bounce used in the lighting simulation tool Radiance. Ambient bounces show the number of diffuse inter-reflections computed by the indirect calculation, since the reflected light, either from the ground or from other buildings is not included in the direct calculation, see *Figure 2.*

The use of vertical daylight metrics is still not widely acknowledged, and the VSC is mainly used in Hong Kong and UK, where it is strongly supported by the research of Littlefair since 1991. It has been proposed for use in Sweden by Paul Rogers (Rogers, et al., 2015) and is slowly gaining interest from city planners and developers. Originally it was used to assess the impact of new-built constructions on the daylight access to existing structures, but now the potential of the VSC in early stage design decisions is recognized. However, as for the DF, VSC is insensitive to orientation. To some extent this is "misleading" to natural human daylight design perception from the cardinal directions, but this is due to the diffuse sky used for calculation. One must remember that sunlight exposure is not studied with VSC.

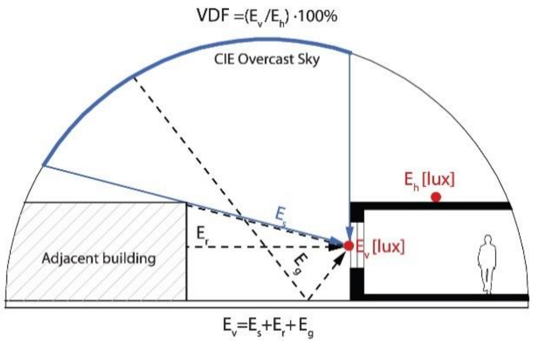


Figure 2 Distinction between VDF and VSC

2.1.4 Sky

The calculation method for the Daylight Factor (DF) and the derived metrics in temperate climates are based on the CIE standard overcast sky, which was developed by the International Commission on Illumination. The CIE standard overcast sky is a sky model with a rotationally symmetric luminance distribution where the zenith is three times brighter than the horizon, see *Figure 3* below.

$$L_0 = \frac{1}{3} \cdot L_z \text{ [cd/m}^2\text{]} \quad (5)$$

Where L_0 – luminance at the horizon and L_z – zenith luminance [cd/m²]. The luminance distribution is constant horizontally and varies only with the elevation of the view.

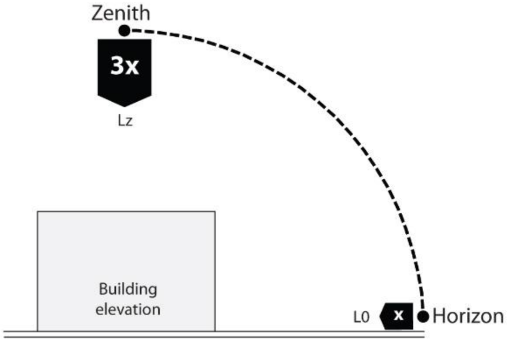


Figure 3 CIE standard overcast sky

Among the three summed DF components, the Sky Component (SC) usually has the greatest impact on the total illuminance calculated at a point. The fundamental daylight equation below describes the contribution to the illuminance on a point on a surface from a small patch of sky:

$$E_{ki} = L_i \cdot s_i \cdot d_{ki} \text{ [lux]} \quad (6)$$

Where i – sky zone; k – receiving area; L_i – luminance of the sky zone; s_i – angular size of the sky zone; d_{ki} – daylight coefficient, which is the fraction of the skylight emitted to the work plane (Tregenza & Wilson, 2011).

The illumination from the sky is not merely dependent on the area of the visible sky, but also largely influenced by the exact sky zone position in the full hemisphere (City University of Hong Kong, *Methods for Daylight Factor estimation*).

Furthermore, Lambert's cosine law explains the relation between the luminous flux of the sky and the illumination on surface dependent on the angle, where illumination of a surface is directly proportional to the cosine of the angle, and maximum illumination is obtained when light falls along the normal of the surface:

$$E = \propto \cos\theta \quad (7)$$

Where E – illumination of a surface [lux]; θ – angle between the direction of the incident light and the surface normal [°].

Li, et al. (2009) added that the most useful light comes from a cone of light 100° centred to the normal of the glazing. According to their observations and considering the advised limitation of θ ≥ 25° (CIBSE, 1998), the unobstructed sky at the 25° of this cone is sufficient to generally provide satisfactory daylit interiors. The obstruction angle is measured from the middle of the window to the mean top point of the opposing obstruction (see *Figure 4).*

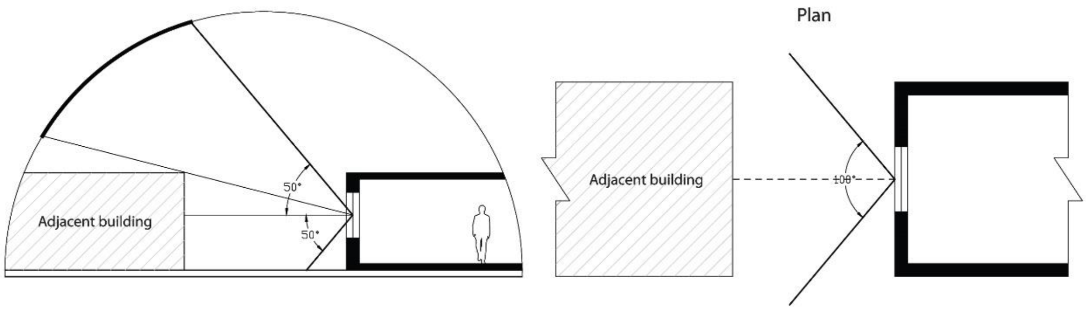


Figure 4 100° cone of light normal to window

External frontal or perpendicular obstructions limit the direct skylight into the room. By limiting height rather than the width of the obstruction, the skylight is admitted deeper into a building, increasing the SC.

The same VSC value does not represent the same building context due to different sky patches visible between tall blocks or low urban canyons. Hopkinson, Petherbridge and Longmore (1966) clarified that in a building with perpendicular obstructive walls the skylight is limited only to one side of the building, and so the penetration of direct light in the room is not severely affected. With this in mind, in large scale urban planning, buildings should be placed at right-angles rather than parallel to each other.

2.2 CBDM and DF

The Daylight Factor is a convenient metric to informed design decisions where an overcast sky is predominant. As the DF addresses a single standard overcast sky condition, it is arguably less useful in climates where sunny days are prevalent (New Buildings *Institute Daylight Pattern Guide: Analysis Methods, n.d.*).

On the other hand, there are Climate Based Daylight Modelling or Metrics (CBDM) such as Daylight Autonomy (DA) or Useful Daylight Illuminance (UDI). CBDM are based on realistic sun and sky conditions from historical weather and climate data observations, specific to the hours of the year and unique to location and orientation. Since climate-based metrics are focused on holistically modelled daylight – the illumination effect of vast variations of sun and sky together, the results are a valuable tool for detailed architectural design analysis to predict shifting luminous quantities and hereby regard occupancy patterns. (Mardaljevic et al., 2013).

Nevertheless, despite the advantages, CBDM modelling and simulation tools are mainly used by experts and researchers. Even though various lighting simulation applications help to simplify the process, a general user is not able to provide valuable and trustworthy results as noted by Mardaljevic & Christoffersen (2013). To fully utilize such complex information and tools, exact information about the building geometry and usage is needed, which might not be clearly defined in the early design phases (Iversen, et al., 2011). Also, due to specific location and other parameters, the results cannot be carelessly generalized and compared, especially in an elongated country like Sweden.

The DF method, even though it is a primitive tool, still provides handy and easy-to-calculate confirmations based on the fundamentals of daylighting design. The calculated or simulated results can be certainly validated in real buildings using illumination meters (New Buildings *Institute Daylight Pattern Guide: Analysis Methods, n.d.*).However, the lack of direct and reflected sunlight in DF calculations may result in excess sunlight, heat and glare issues under clear sky conditions as stated by Iversen, Nielsen and Svendsen (2011).

The Daylight Factor represents a conventional and time-efficient way of daylight evaluation despite the lack of site-specific information or weather conditions. It is still perceived as the most widely used daylight assessment method in the building industry, and for that reason, the DF is the metric used in this study for development of an early stage urban planning and architectural design guideline.

2.3 Rules of thumb for VSC and DF

Rules of thumb are used to simplify complex phenomena. Their application can be defined as rough but practical methods of procedure. In the daylighting context, several rules of thumb can be found advising on building form and room design factors such as depth, floor area, window heights and widths, all related to more effective daylighting.

A couple of basic rules of thumb were identified as a part of the literature review, which can be applied and compared to this study. CIBSE (1998) Desktop guide to daylighting for architects identifies the six most common of them. Among others, it notes that external obstructions should not make an obstruction angle higher than 25° above the horizon, and areas, where there is no direct view of the sky, have low daylight levels.

The BRE Trust Site Layout Planning for Daylight and Sunlight guidelines by Littlefair (2011) present VSC target values derived from a low density suburban housing model corresponding to approximate agreement with an infinitive sky view angle and can be interpreted flexibly, (see *Table 1)* (Greater London Authority, 2013). It must be noted that the exact amount of daylight required is dependent on the function of the room, and BRE values are targeted to an average DF of 2%, hence to guide for the Swedish BBR (Boverkets byggregler) requirements adjustments must be made.

Table 1 VSC and obstruction angle classification by BRE

VSC or Obstruction angle θ		**Daylight conditions**
VSC > 27%	θ < 25°	Conventional window design usually satisfactory
15% < VSC < 27%	25°< θ < 45°	Larger windows / changes in layout are usually needed
5% < VSC < 15%	45°< θ < 65°	Difficult to provide adequate daylight
VSC < 5%	θ > 65°	Achieving reasonable daylight is often impossible

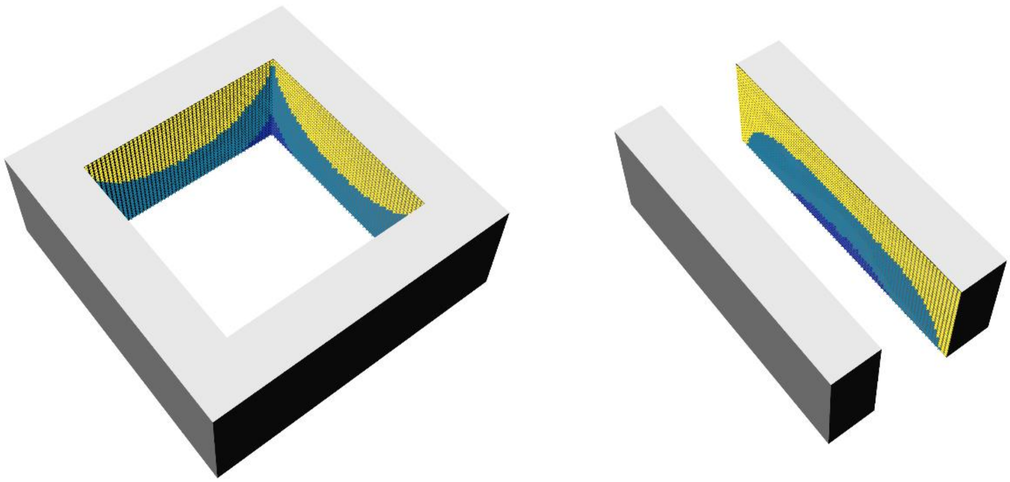


Figure 5 Typical VSC distribution on façade in A: O-shape; B: II-shape. Legend according to the Table 1.

A typical illuminance distribution on a façade by BRE classification is represented in *Figure 5*. It can be observed that the darkest area per façade is dependent on the building shape: in long urban canyons, the middle section has the lowest illumination, whereas in buildings with walls at 90° angle, the corner is the most shaded and therefore critical part.

From the graph in *Figure 6* below, the VSC based on known obstruction angles can be read, however it assumes a horizontal roofline and neglects any obstructions above the window. It does correspond well with VSC classification by BRE in *Table 1*, since an obstruction angle of 20° requires VSC of 27% here.

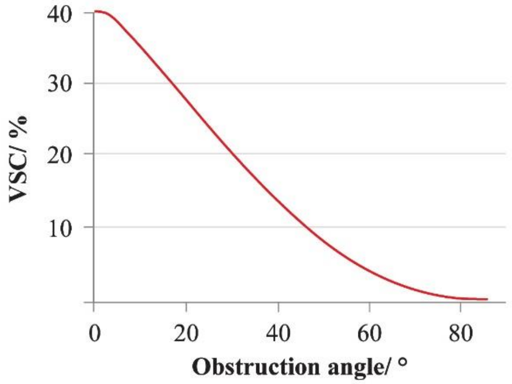


Figure 6 Function of VSC and angle of obstruction (Tregenza & Wilson, 2011)

There is also a simple rule of thumb on calculating the average DF on the vertical outside window surface (VDF_w) based on the unobstructed sky view angle (α) in degrees that includes both direct and reflected light according to the simple formula below:

$$VDF_w \approx \frac{\alpha}{2} [\%] \qquad (8)$$

Estimating 5% from ground reflection conversion factors from VDF to VSC are also provided by Tregenza & Wilson (2011).

Several graphical methods for a manual VSC determination have been developed such as the Waldram diagram and BRE protractors and nomograms. They can provide rather quick analysis and reliable results where geometry cannot be easily simplified.

Detailed development plans of new city developments accept higher urban density thus increasing difficulties to achieve the required daylight levels in buildings. Already in 1998 Littlefair had remarked the impact of site layout on daylight conditions, especially in dense urban areas at high latitudes. He suggested to limit the obstruction angle to a value corresponding to 66.5° minus the latitude of the site to guarantee at least 3h of sun per day all year round. Following that, the maximum obstruction angle in Malmö would be approximately 15°, which is utterly unlikely in dense urban city developments.

In his study, DeKay (2010) remarked that with higher latitudes, the DF baseline must be increased due to decreased exterior daylight availability, hence at latitudes above 54° DeKay suggests DF average to be 4.5%, providing 215 lux (20 fc) illumination at 85% of the working hours (DeKay, 2010).

Even though the DF method itself cannot be classified as a rule of thumb due to many aspects and calculation steps involved, some building standards specify the lowest target value based on certain room and window dimensions. One of the examples is the Swedish Standard SS 91 42 01 specifying minimum glazing area (SIS, 1987), more described in paragraph *2.4 Building standards.*

The CIBSE Daylighting and window design guide categorizes DF as shown in Table 2 below:

Table 2 DF classification by CIBSE (1999)

Average DF	**Daylight conditions**
DF > 5%	Well lit. Artificial lighting during daytime is normally not required. Large glare and excessive solar gain probability.
2% < DF < 5%	Adequately lit, but supplementary artificial lighting is usually needed.
DF < 2%	Not adequately lit, artificial lighting is required.

BREEAM advises a minimum average DF across 80% of relevant area at the workplane height, classified by use and based on latitude, see *Table 3*.

Table 3 DF criteria in residential institutions as in BREEAM SE

	Average DF required by latitude [°]	
Area type	**55 – 60**	**≥ 60**
Kitchen	2.1%	2.2%
Living rooms, dining rooms, studies	1.6%	1.6%
Non-residential or communal occupied spaces	2.1%	2.2%

2.4 Building standards

In Sweden major towns are located from high 55° to 67° N latitudes. This means that in the north of Sweden midsummer sun never sets. Winters are long and dark even in the Southern part with only six hours of sunlight during a day. Correspondingly, the intensity of daylight is rather varied throughout the year.

Swedish building regulations BBR

The Swedish building regulations has divided the country into four zones for certain energy demands to be fulfilled. Nevertheless, the requirements on daylight in indoor spaces are the same across the whole country. The requirement on daylight is formulated like this (our own translation):

> Rooms or separable parts of rooms where people stay more than temporarily should be designed and orientated so that good access of direct daylight is possible, if this is not unreasonable regarding the proposed use of the room.
>
> > *General advice*
> > For calculation of the glazed window area a simplified method according to SS 91 42 01 can be used. The method is valid for room sizes, window glass, window sizes, window placement and obstruction angles according to the standard. Then, the glazed window area should be at least 10% of the floor area. It means that a daylight factor of about 1% if the conditions of the standard are met. For rooms with other conditions than those stipulated in the standard, the glazed window area should be calculated for the daylight factor of 1% according to the appendix of the standard. (BFS 2014:3).

The Swedish Standard SS 91 42 01 (SIS, 1987) that the current daylight requirements in the BBR refer to specifies the minimum accepted glazing area for rooms. In order to use the standard, certain geometrical constraints must be met. For example, rooms must be side-lit, have certain width and depth range, certain window dimensions and placement, and the glazing and obstruction angle (θ) must be according to the standard. Further, glazing should be clear (two or three pane windows). If these conditions are met, a flat-rate value of 10% glazing-to-floor ratio is specified as the lowest threshold to fulfil the daylight requirements in the defined room geometry given that $\theta \leq 20°$. The standard is valid up to an obstruction angle of 30° but for 30 degrees, the glazing-to-floor ratio should be 12,5%. For values in between, a linear relationship is assumed.

If the geometrical constraints are not met, the standard points to the daylight factor method in order to check daylight compliance. The standard shall therefore be seen as an alternative and simpler way of ensuring that the point daylight factor is at least 1%. It must also be seen in the historical context: During the time when the standard was developed, the alternative way of calculating the daylight factor was via graphical methods using daylight protractors on plans and sections of the room, and this could be rather tedious work. This was probably the whole idea of developing the standard – a method faster to use than the daylight factor. Therefore, the geometrical constraints are necessary to follow in order to ensure that the 10% glazing area will actually provide a 1% daylight factor.

During many years, the building legislation only mentioned the simplified method as a way of ensuring the fundamental requirement (good access to direct daylight), but since a few years back, the notion of the daylight factor has been brought back into the code (Boverket, 2017). In BBR, the text in the advice is rather strong, as it is usually interpreted as a requirement.

Today, there is an ongoing project to try to modernize the code. It is not yet clear how the daylight requirement will be formulated in future versions of the legislation, but as a first step it is rather likely that the point daylight factor will give way to for example the median daylight factor (Dubois et al., 2017).

Building certification systems

Miljöbyggnad is a Swedish environmental building classification system that has had a great impact on highlighting quantitative daylight assessment in the Swedish market. The certification process of existing constructions has been revealing. It emerged that many projects do not meet the minimum BBR requirements thus forcing the shift from once constant focus on energy and materials back to daylight and well-being.

Miljöbyggnad currently supports both hand calculated or simulated (point or median) DF values and glazing area based method, SS 91 42 01. When using computer simulated DF, it is accepted with a deviation of 0,2% to the required value, thus indicating discrepancy between the methods (SGBC, 2015).

The building assessment methods often encourage to follow the national daylight standards prior to their benchmarks largely due to generalisation for worldwide application. Many countries have altered the most common international building certification systems to their standards, however, in most of the countries, the regulated daylighting thresholds are even lower than specified there.

The Miljöbyggnad daylight criteria are based on the BBR and are therefore mandatory, whereas international certification systems BREEAM or LEED have daylight credited as a voluntary part of their indoor environment assessment. To assure daylight provision various documentation methods are offered, but specific requirements are non-compulsory. Both aforementioned systems have been adapted to the Swedish context, where since 2009 Swedish Green Building Council for compliance with BREEAM requirements, see *Table 3*, is awarding two additional points (USGBC, 2013). Nevertheless, these optional points are rarely aimed for as it would often mean some points lost in energy-efficiency.

Upcoming developments

Mardaljevic, Christoffersen, & Raynham (2013) recognized the necessity for changes in building requirements by proposing that the designed daylight provision must be based on natural daylight availability. In other words, the requirements ought to consider the cumulative diffusive illuminance at the particular location.

Meanwhile many of the leading Swedish architectural and construction firms guided by the Development Fund of the Swedish Construction Industry (SBUF) have contributed to an upcoming comprehensive study of existing Swedish building stock with an aim to guide the authorities in their upcoming building code, as presented by Dubois et al. (2017).

The preliminary findings suggest a switch from the currently used point DF to median DF as the most representative metric, instead of space average DF. *Figure 7* illustrates the calculation methods mentioned.

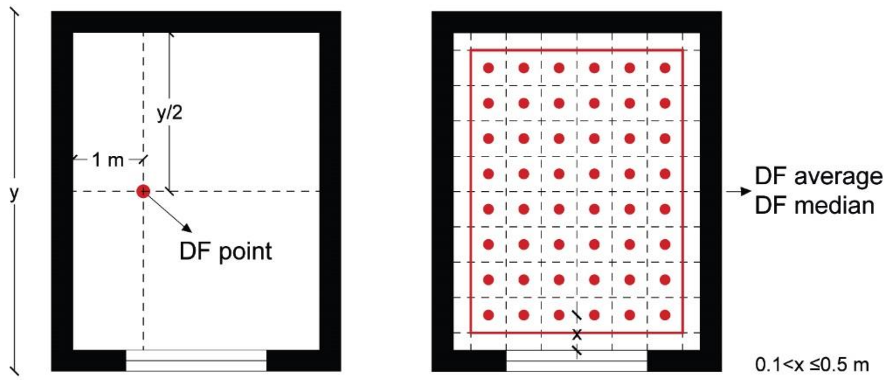


Figure 7 DF point and grid-based DF calculation methods

Assessment of the daylighting metrics

By merely looking at the numbers, it is easy to believe that to meet DFavg of 2% a room must have larger glazing area than for a point or median DF of 1%. Nonetheless it must be noted that a DFavg of 2% could possibly have the same daylight distribution as DFmed of 1% as recognized by Mardaljevic, Christoffersen & Raynham (2013).

They also proved a discrepancy between the DFavg values in an exemplary room with one window, depending on the selected 80% of the total area. The DF results varied within a range of almost 1.8%, whereas median DF was considerably lower but less sensitive to the chosen part of the room due to rather exponential than linear decay of illuminance from the window into the room.

Also, as observed by a quick complimentary study on DF metric evaluation, executed along the main thesis topic in *Table 4* below, the difference between the DFmed or DFpoint to average DF is roughly 50%.

Table 4 Comparison of DF metrics for the standard room shown in Figure 11 at corner placement in O-shape typology

Type	θ/°	DFavg/%	DFmed/%	DFpoint/%	Δ DFmed / DFavg	Δ DFpoint / DFavg
3 - 20x20	20	1.14	0.61	0.73	54%	64%
5 - 20x20	33	0.70	0.34	0.42	49%	60%
7 - 20x20	44	0.39	0.22	0.27	56%	69%
9 - 20x20	51	0.25	0.17	0.18	68%	72%
3 - 30x30	14	1.32	0.78	0.80	59%	61%
5 - 30x30	24	1.02	0.50	0.53	49%	52%
7 - 30x30	33	0.68	0.32	0.39	47%	57%
9 - 30x30	40	0.50	0.27	0.31	54%	62%
3 - 40x40	10	1.42	0.87	0.83	61%	58%
5 - 40x40	18	1.10	0.58	0.57	53%	52%
7 - 40x40	26	0.89	0.42	0.48	47%	54%
9 - 40x40	32	0.71	0.36	0.37	51%	52%
3 - 50x50	8	1.40	0.81	0.86	58%	61%
5 - 50x50	15	1.22	0.70	0.60	57%	49%
7 - 50x50	21	1.01	0.52	0.52	51%	51%
9 - 50x50	27	0.87	0.41	0.44	47%	51%
				Mean:	54%	58%

(Note: The type describes modelled building geometry, for example, in "9 – 40x20" the "9" represent stories in courtyard dimensions 40 to 40 m looking from room positioning.)

Advanced daylight simulation must be used to increase accuracy and eliminate confusion of complex geometry by replacing the manual point DF calculation method with average or median metrics, as suggested in the comprehensive review of Swedish daylight requirements by SBUF (Rogers, et al., 2015).

Additionally, specific requirements related to the grid choice should be given, which would provide information about light distribution in the space (Mardaljevic, 2013).

There is a debate about using CBDM over DF in the building regulations that SBUF argues against due to slow development of current daylight calculation methods among the practitioners.

Nevertheless, the recent Danish building code BR18 has tried to adapt the imminent EU 17037 standard. It is largely supported by research of Mardaljevic & Christoffersen (2013) that emphasizes the practice of daylight availability metrics and weather data. The aim of EU 17037 is to assure good daylight in all spaces not merely to fulfil the generalized minimum targets.

The use of average DF of 2% in BR15, the previous Danish building code, in BR18 has been substituted with specifying 300 lx at minimum 50% of the relevant floor area during half of the daylight hours. However, the rise of the daylighting threshold from current minimum to allegedly good values elevates concerns about the risk of large amount of spaces failing the new requirements, especially in the existing building stock.

Yet the uncertainty of threshold values and lack of expertise are tolerated by permitting other calculation approaches to be used for the documentation, such as the glazing-area based method. Alternative methods may be applied if it can be proved that the spaces are adequately illuminated (Ministry of Transport, Building and Housing, 2018.). This final statement leaves a large hole in the BR18 for free interpretation on daylight requirements.

The target threshold values

According to SBUF report by Rogers, Tillberg, Bialecka-Colin, Österbring & Mars (2015), the balance between daylight and energy-efficiency in a building largely depends on the set limit of the daylight factor. Considering the minimum threshold at DFpoint of 1% and energy conservation as stated in the Swedish building code BBR25 (Boverket, 2017), architects and planners through careful studies ought to determine an optimal window-to-wall ratio.

A majority of building users consider well daylit space at an illumination of 300 lux to be adequate, hence both Mardaljevic and Littlefair looked past the oversimplification of daylight requirements in Europe at the principle of one-rule-fits-all. They estimated the target DF based on mean diffuse illumination, where in Stockholm E_{dh} 12100 lux would correspond to DF 2.5% measured at point on the work plane with the desired illumination of 300 lux. Even though the values mentioned are considerably too high to be applied as a standard due to rather impossible way of achieving them in dense urban settings, it must be noted that at average DF of 1% user behaviour would often call for electrical lighting (Mardaljevic, et al., 2013), (Littlefair, 2011).

Nevertheless, in the search for better standards, it is crucial for the industry to implement and assure proper design to meet the current daylight regulations. Additionally, it would be good practice to protect the interests of the influenced building occupants by securing their rights-to-light as in England and in Wales (RICS, 2010). Even though the exact boundaries of the law are debateable (Chynoweth, 2005), the notion forces architects and urban planners to respect the present conditions. Most of the parties involved – municipality, architects, electrical lighting industry, HVAC and other consultants, construction companies and habitants have reasonably different goals and expectations towards the daylit environment (Rogers, et al., 2015).

2.5 Literature review

The following literature review was conducted prior and during the study, which can be divided into five sections to include information gathered of existing research:

- General factors influencing daylight in buildings
- Existing research on vertical illuminance assessment metrics of Vertical Sky Component and Vertical Daylight Factors as a describing element of interior illuminance levels
- The impact of reflectance from surfaces in close context
- Optimal façade design in terms of glazing area
- Analysis of urban fabric in relation to building typology and courtyard design.

Daylight influencing factors

DeKay in 1992 performed a comprehensive study of available planning tools to conclude that all were to control sky exposure, but none of the reviewed tools proved to be fully reliable to quantify daylight within the buildings (DeKay, 1992). In a study from 2010 he identified the important building block parameters to be considered for daylight access and to establish the daylight as a guide for urban design: atria shape and proportion and building thickness (DeKay, 2010).

The fact that geographical location must be considered in urban design was once again observed by Sundborg (2010), who distinguished the importance of wide spaces, especially at high latitudes, that has become limited in denser neighbourhoods, to allow sunlight access throughout the year.

Vertical illuminance assessment

Li, et al. (2009) developed a step-by-step calculation procedure to compute the VDF on facades with large external obstructions. The study was based on long urban canyons as one of Hong Kong's main skyline features. It is remarked that the method applies to simple skyline forms, whereas for complex settings it may lead to error.

As a conclusion of the comprehensive study, eight steps towards VDF estimate were presented. The results are based on a predetermined ground to unobstructed horizontal illuminance chart, known upper and lower obstruction angles, reflectance of surrounding surfaces and sky component computed as the sum of individual sky subdivisions visible from the point on the façade of interest. The developed VDF assessment model was compared to other methods and the results were in good agreement with Radiance simulations.

The impact of reflectance of surroundings

External obstructions influence the daylight performance in two aspects: amount of unobstructed sky and reflected light from obstructions and ground, hence narrow spacing between the buildings causes severe daylighting issues particularly at the lower floors. Most of the daylight reaching windows at the bottom floors is primarily through reflected light from the opposing façade, but for large VDF values, the sky component is the dominant factor. In heavily obstructed environments, the ground reflection is significant, as noted by Li, et al. (2009).

Iversen, Nielsen and Svendsen (2011) observed that with higher reflectance of the opposite façade, more of the light will penetrate in the space. However, the same VDF achieved with different reflectances of the opposing facade would not result in the same profile of the illuminance level through the room. With an obstruction of higher reflectance there is greater proportion of reflected light, therefore rays bounce deeper in the space. To achieve the same VDF with lower frontal obstruction material reflectance value, the sky component must increase therefore to increase the direct sky illumination.

Shaples & Lash (2004) studied closed, four-sided atria with black and white facade bands. They concluded that the VDF and the IRC results were rather unaffected to the reflectance distribution on the surface of the façade at the top half of the atrium well.

Both Iversen, Nielsen and Svendsen (2011) studying urban canyon and Samant (2011a) assessing enclosed atriums came to the conclusion that DF on the first floor level appears to be slightly lower than on the bottom level, due to ground reflected light.

Samant (2011) emphasized the role of atria and surrounding surfaces in daylight distribution within the building. Nonetheless, Samant found the DF to be more affected by the size of atrium in terms of width, length and depth (Well-Index) than the average surface reflectance values.

The aim for optimal window-to-wall ratio in dense urban setings

Samant (2011) performed a literature review on atria. It was concluded that the glazing area should vary between different floors in the building, and smaller windows are needed at the top floor levels since this is where most daylight is naturally available.

The literature study was followed by a parametric study on window sizes and calculated room depth in order to obtain an average DF of 2% in the adjoining space. Samant (2011b) realised that the DF is not influenced by glazing distribution beyond 3 meter depth, where the DF is significantly reduced.

Iversen as a part of her PhD thesis about developing a simple assessment tool for daylight performance in urban scale, presented four papers (Iversen, 2013). Three of them aid the decision-making process looking from climate-based observations, but Paper I is a study where the densities of urban building layout, external surface reflectance values and façade window areas were varied on an infinitive urban canyon model under CIE overcast sky (Iversen, et al., 2011).

From the results of all four papers a four-step method and a computer tool EvUrbanplan, a look-up tool of a simulated database, was developed to evaluate facades in an urban context and relate the density of the city to the façade WWR and the DF inside. The input parameters to the tool were width of the urban canyon, height and reflectance of the opposing building and the target illuminance at critical depth in the room.

Unsurprisingly, it was found that larger WWR corresponds to better indoor illuminance. On the other hand, Iversen, Stromann-Andersen and Sattrup also remarked the generally low reflectance of windows, meaning that increasing window area could result in a lower overall façade reflectance. Therefore, an iterative approach should be considered (Iversen, et al., 2011).

In the context, Erlendsson (2014) learned that daylight autonomy levels were found to peak at a glazing-to-wall ratio of 65-75% and gradually fall with lower glazing-to-wall ratios (GWR) caused by a decrease in reflected light within the atrium.

Daylight in courtyard building morphology

Erlendsson (2014) investigated atria design and discovered that the shape of an atrium is fundamental and constructing the top wider than base was found to have substantial effect on the daylight autonomy because of the less obstructed sky at the bottom floor levels, especially at the higher latitudes.

Based on the same observations, a similar conclusion was made by both Samant (2011a), DeKay (2010) and Du & Sharples (2009), where the latter noted that the vertical illuminance on the centre line of an atria wall varies exponentially from top to bottom, but on the floor level the central 40% of the total wall area has the largest potential for natural daylight in the adjacent spaces.

While Erlendsson (2014) analysed shape and configuration of top-lit all-sided atriums exclusively, Samant (2011a) principally selected four-sided atrium as the worst-case scenario for daylight settings to be analysed.

Additionally, it was remarked that among other shapes the daylight uniformity is highest in a circular atrium, meaning that the dark and shaded corners are eliminated from the design (Erlendsson, 2014). However, due to economical and practical reasons mostly rectangular shapes are present in a city fabric.

DeKay (2010) studied rectangular atrium blocks of various layouts, but permitted side-lit typology, concluding that by having one or two sides glazed will usually provide more of the light than solely top-lit openings. Nevertheless, the C, E, F, and H shaped buildings are often dimensioned following generalized massing rules with no strong confirmation of providing sufficient daylight levels at the lower floors, even though it has been confirmed that additionally side-lit courtyards provide more daylight.

Even though DeKay (2010) was considering open courtyards, the general findings apply to conditioned atriums as well. Based on roof glazing and structure the light transmission relative to open courtyard may decrease by 20 – 80% (Erlendsson, 2014).

Rogers (1999) in his thesis analysed changes of sky view-factor as a result of building and courtyard shape and obstructions. It was noted that for wide yard proportions there is large discrepancy in sky-view between U-shape and enclosed configurations due to added vertical aperture, where in narrow settings the difference is minor. Also, at lower heights shift in sky view-factor between enclosed, U- and L-shaped configurations is limited.

Du & Sharples (2009) looked at the impact of well geometry in atria of square and rectangular forms. They noted that changes in width to length ratio has larger impact on VSC in the central area of the façade. Near the corners the VSC due to more obstructed sky is largely sensitive to building height.

Instead of closed courtyards Iversen, Nielsen and Svendsen (2011) analysed urban canyons – infinitely long streets with buildings at the opposite sides. They reached the same conclusion, where VDF was to decrease by smaller distance between the buildings and larger obstruction angle from the opposing building.

Summary

The literature studied and summarized above is merely a part of many sources revised and reviewed that guided towards the structure and limits of this thesis. This study aims to clarify and simplify the possible use of Vertical Sky Component. From the architectural perspective, better understanding of the VSC use and relations with interior daylight illuminance, could result in better daylighting design as the simple simulation and analysis can be made early in the project by merely including the surrounding geometry.

3 Methodology

The project was carried out in five phases according to *Figure 8* below.

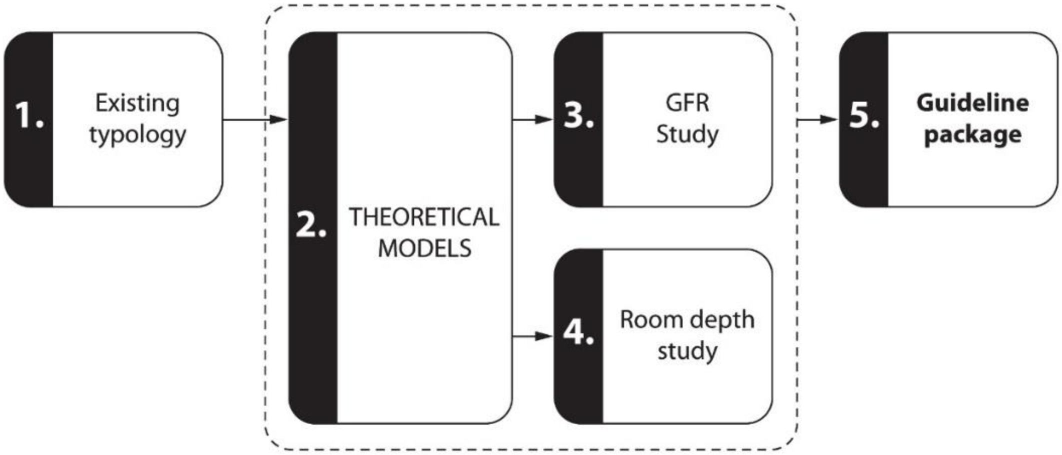


Figure 8 Methodology overview

Firstly, Malmö courtyard building typologies were identified as typical samples of Swedish urban development over various time periods.

The second part was a parametric study to test the relation between the DF and the VSC in five simplified theoretical building forms, based on found typology representation. As a part of the study the courtyard proportions and size and building height were varied. The effect of shading from the context was studied by simulating and comparing two different room placements on the ground floor level – best and worst case scenarios – to test the bounds and potential of the whole ground floor façade in focus. Moreover, the influence of the ground reflection was tested on the same geometries.

In part three, a study of different glazing-to-floor ratios was performed on the selected hypothetical models.

The fourth part of the study investigated the effect of the room depth to understand the impact on the VSC – DF relation.

The final fifth stage was to develop a guideline following the aim of this study and to present the potential route to application.

To conduct this study the following computer tools were used:

Rhinoceros & Grasshopper

Rhinoceros is a 3D modelling tool used to create, modify and visualize both simple and complex geometries. It can be a powerful tool, especially when connected to plug-ins like Grasshopper, a visual programming language integrated within Rhinoceros (Davidson, 2018). This flexible open-source tool uses component combinations to build models, edit them and even perform parametric studies. When linked with other plug-ins like Ladybug & Honeybee it can be used to simulate various parameters and also aid the analysis of the output data. Both Rhinoceros and Grasshopper were used during the second, third and fourth phases of this study.

While Rhino was used to model only the room geometry, Grasshopper was used to parametrically build each of the considered typologies.

Honeybee & Colibri (TT-toolbox)

Honeybee is an open-source plug-in, designed to perform environmental analysis while connecting Grasshopper with other simulation engines. Specifically, it creates, runs and visualizes the results of daylight simulations using Radiance, energy models using EnergyPlus/ OpenStudio, and heat flow through construction details using Berkeley Lab Therm/Window (Ladybug Tools LLC, 2017-2018). Honeybee was used to conduct all the daylight simulations in our study.

Additionally, Colibri within the T-toolbox plug-in was exploited to handle all the data, by collecting all the output results for each iteration that comes from the defined Grasshopper parameters to create a data.csv file. In this way, it enables a direct link to Microsoft Excel, facilitating the process of data export.

3.1 Phase 1: Malmö typology

A quantitative study was conducted by investigating existing courtyard typologies in Malmö built during different time periods of the 20th century. Most of them were spotted out from the inventory of buildings constructed respectively from 1945-1955 and 1965-1975, published by Länsstyrelsen Skåne Län och Malmö Kulturmiljö (2001; 2002). Information on dimensions and height of the buildings was extracted from a rough estimation using the Malmö stad website and Google Maps (Malmö Stadsbyggnadskontor; Malmö stad).

3.2 Phase 2: Parametric building configuration study

Based on the first phase observations, the typologies in *Figure 9* were defined as the starting point geometries for the subsequent analysis. The idea was to begin from a closed courtyard and then slowly transforming the configuration towards a more open one.

It was considered important to study two rooms on the ground floor for each of the types, which would depict the character of the whole ground floor. The position of the room was varied according to the typology, representing the worst and the best case in the ground floor level in terms of daylight illuminance. The ground floor was chosen as the worst-case scenario of the whole building, due to lowest sky-view factor possible.

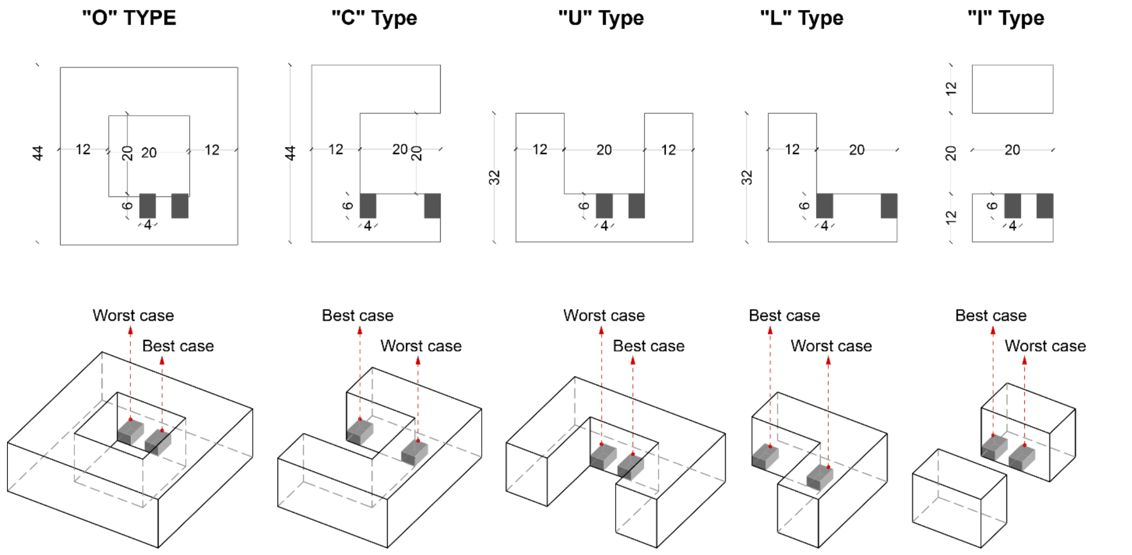


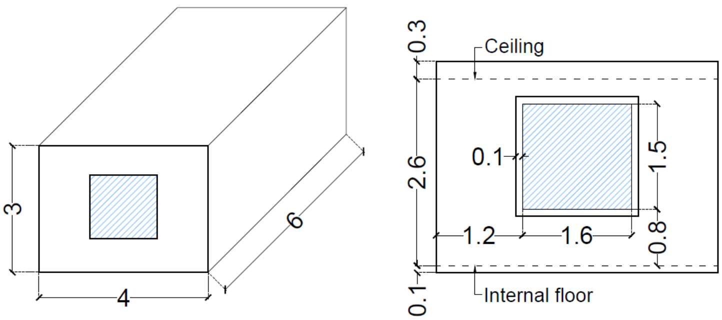
Figure 9 Building typologies

In all of the cases, the room geometry was fixed as the first aim was to understand the influence of the varied building volumes on DF. The examined room had a basic box shape (*Figure* 11), with only one window 80 cm above the floor level, positioned in the middle of the external wall, with the assumed thickness of 0.40 m. The size of the window was based on minimum BBR recommendation of 0.1 Glazing-to-Floor ratio (GFR). Moreover, the visible transmittance of the window was set to 0.7. Other room properties such as surface reflection were assigned based on standard values as Figure 11 shows.

Additionally, in dense urban setting, the property developer or architect has minor influence over the adjoining environment concerning the materials hence reflectance values of surfaces and objects nearby. However, where the whole building block is to be developed, a typical ground reflectance of 0.2 (*Figure 10*) can be easily increased as a design decision, and therefore the effect of increased value of 0.3 was studied to estimate illumination increase indoors.

Figure 10 Visual representation of typical ground reflectance of 0.2 and improved 0.3 (JALOXA, 2013)

The specularity and roughness of all surfaces was assumed to be 0, as they were considered to be Lambertian surfaces, reflecting light equally in all directions (Larson & Shakespeare, 2003).



Surface reflectance

Ceiling	0.8
Internal wall	0.7
Window frame	0.5
Floor	0.3
External wall	0.3
Ground	0.2

Window visual transmittance	0.7

Figure 11 The standard room properties from left to right: A – external geometry; B – internal measurements; C – the optical properties

Only the room geometry was modelled in Rhinoceros, while the rest of the building context was parametrically constructed in Grasshopper. Three building courtyard proportions were studied for each of the typologies examined, specifically 1:1, 1:2, 2:1, referring from the façade of the room position (*Figure 12)*.

In addition, two inputs were varied for every proportion:

1) number of stories or building height from 9 m to 27 m assuming a story height of 3 m
2) the inner dimensions of the courtyard varying from 20 m to 50 m or 100 m

This resulted in a total of 16 combinations for each room location (centre – corner or inner – outer) for every defined courtyard ratio. The range of obstruction angles was from 4° to 51°.

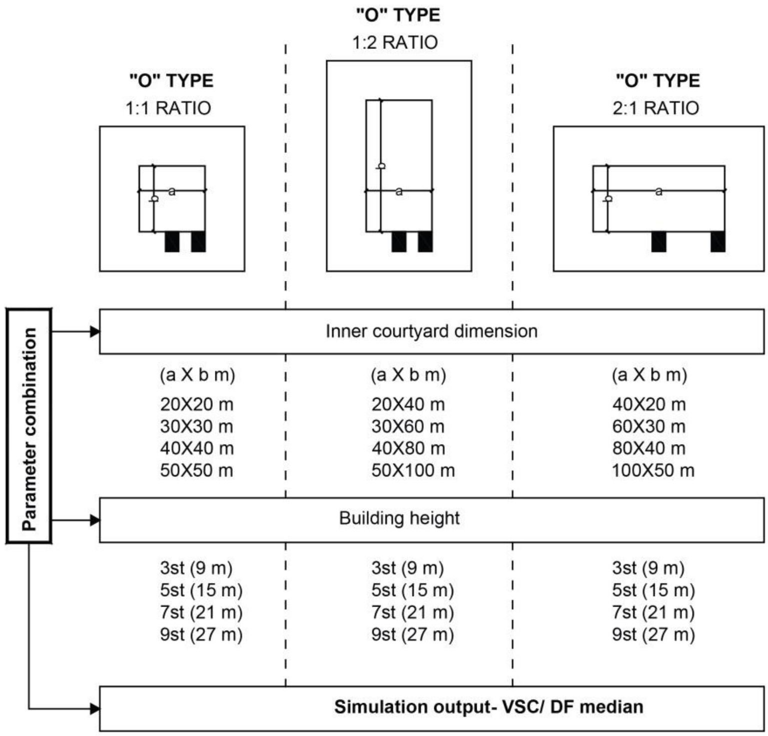


Figure 12 Typology parametric configuration. *Note: st = number of stories*

Honeybee was used to simulate and calculate the average VSC of the façade of the standard room and the corresponding median DF (DFmed) in the room. The average VSC was evaluated for three different parts or areas of the façade, as in *Figure 13*:

1) the average value for the whole bottom floor façade where the room was placed, area varied under the parametric study – VSC Storey
2) the fixed 3 x 4 m façade area of the standard room as viewed from outside – VSC Room
3) the average VSC incident on the fixed window area, 1.8 x 1.7 m – VSC Window.

The location of the measurement point and visualisation of the results must be re-evaluated to fit this study and better represent VSC/VDF results in less uniform settings. Therefore, initially, we used all three to find the optimal solution.

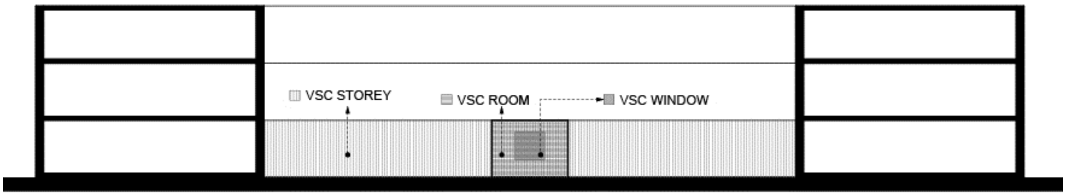


Figure 13 Facade selections for the average VSC Storey, Room and Window estimates

The DF in the room was calculated at an elevated work plane 0.8 m above floor level with a 0.5 x 0.5 m grid resolution, and the area within 0.5 m distance from the walls was not considered.

The VSC was analysed 5 cm from the corresponding surface area of the façade at a grid of 0.5 x 0.5 m for VSC Storey and Room and 0.1 x 0.1 m for VSC Window.

Two sets of parameter settings were developed; one for the outdoor VSC analysis and one for the indoor DF calculations. Since Radiance simulation can become time consuming, a pre-study of Radiance parameters was necessary to understand their influence on the simulated values.

Prior to the parametric study, a benchmark study without the building in context was performed to assess the maximum DFmed and VSC values for the established simulation settings.

3.2.1 Radiance parameters

As the only source of light for both the VSC and DF calculations is the CIE standard overcast sky, mainly the ambient (-a..) calculation parameters were investigated. Direct (-d..) options were excluded as they were considered insignificant for this study.

A sensitivity analysis on Radiance parameters performed by Dubois (2001) showed significant variations in the DF results in the same room based on different calculation settings. According to Dubois (2001), the greatest precision was obtained by combining high accuracy settings, but as Mardaljevic (2003) states, it is unlikely to hit on the ideal combination that delivers the best compromise between speed and accuracy.

It must be noted that Radiance uses hemispherical sampling based on statistical Monte Carlo approach, sending samples in random directions searching for the light source, when the latter is unknown (Mardaljevic, 2011). As this process is stochastic, happening at points every now and then across a scene, the results will vary even if exactly the same model with the same options is simulated several times. This effect is inevitable both due to the randomized probability approach and the interpolation. Matusiak, Onarheim & Gruner (2015) concluded that depending on external obstructions an average error of ±10% from benchmark measurements can be expected, moreover, there is a tendency for overestimations. Same observations were made by Dogan, Reinhart & Michalatos (2004).

In order to minimize the “error” or difference observed when running the DF simulation of the same Rhino geometry settings multiple times, we used rather high accuracy settings in our study. Nevertheless Dubois (2001) noted that by increasing all the (-a..) parameters except the (-ab) the total illuminance values are decreased.

To sum up the findings of literature review presented in the *Appendix A*, the optimal simulation options that generated reliable results with acceptable average error range of less than ±10 % within reasonable simulation time were chosen as shown in Table 5 below.

Table 5 Selected Radiance parameters for DF simulation

Radiance parameters				
-ab 6	-ad 1600	-as 400	-ar 300	-aa 0.1

Based on the selected Radiance parameters, a series of computer simulations were carried out and finally, the relation of the VSC and the DF median for each of the cases was plotted, using Excel.

The discussion on radiance parameters above is relevant to DF and not to VSC as the (-ab) is set to 1 when calculating VSC. The major contributor of the total illuminance on the façade is from the direct sky component, so VSC is rather insensitive to the change of rendering options, only ambient divisions (-ad) 512 was considered.

3.3 Phase 3: The impact of the Glazing-to floor-ratio

After the second phase, where the GFR was set to be 0.1, the next step was to investigate the impact of different GFR’s on the VSC-DF relationship. A GFR of 0.1-0.2, with 0.025 increment, were tested as reasonable values for residential typologies. It should be noted that applying the same GFR increment does not mean that the same amount of glazing area will be added to each case. However, as *Table 6* and *Figure 14* illustrates, the added glazing area for each of the considered steps was between 0.5-0.7 m^2.

Table 6 Glazing area parametric input

Window type	**W0**	**W1**	**W2**	**W3**	**W4**	**W5**
Glazing area(m^2)	2.4	3.07	3.6	4.2	4.8	8.05
GFR/WWR	**0.1**/0.26	**0.125**/0.34	**0.15**/0.41	**0.175**/0.47	**0.2**/0.52	**0.34**/0.87

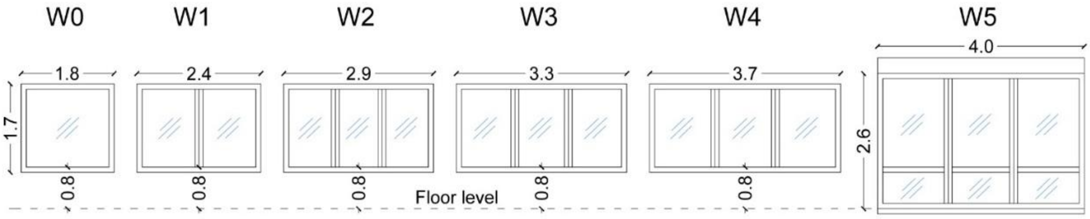


Figure 14 Parametric window design

Different from the previous phase, the varied GFR's were applied to only one typology, the one which was concluded to have the most representable VSC-DF relation. Finally, a maximum value of GFR 0.34, which corresponded to WWR of 87%, was evaluated in order to pinpoint the greatest possibility of daylight availability.

3.4 Phase 4: The impact of room depth

Apart from the window size, architects and building designers can easily consider and influence the room size. The depth of the room in particular is an important factor when it comes to daylight performance. Thus, the width of the room was kept fixed as in the previous phases and four different room depths were examined as *Table 7* illustrates. The window size was not changed for this investigation, and the base window, W0, was considered. Realizing how this parameter would change the VSC-DF relation was the aim of this phase.

Table 7 Room depth parametric input and corresponding GFR

Room depth	4 m	5 m	7 m	8 m
GFR	0.15	0.12	0.085	0.075

4 Results

This chapter presents selected results of this study. In particular it focuses on the impact of the Vertical Sky Component, measured on the façade section, on the Daylight Factor in the adjoining room.

The results are presented according to the five phases mentioned in the methodology section. The results show the flow and derivation of the findings, each referring to a different aspect or parameter studied in order to answer the research question of the thesis.

Phase 1 presents the initial studies of the Malmö building stock. It gives an overview of common building block configurations found in Malmö as a basis for the following parametric study.

Phase 2 is the core of the thesis. This section shows the results of the comprehensive parametric study of the VSC to DF relationship based on five simplified courtyard type buildings, where building height, width and length was varied as well as courtyard ratio and ground reflectance.

Both Phase 3 and Phase 4 supplement the results obtained during Phase 2, by running parametric analysis on Glazing-to-Floor ratio and room depth.

At the end of this chapter, a way to interpret the results in form of an urban design guideline for better daylight provisions based on VSC simulations is presented.

4.1 Phase 1: Malmö typology

This section gives an overview of common city building blocks found in the city of Malmö, Sweden. Parameters in terms of height, width and length were assessed to form the basis for the theoretical model and parametric input design studied in this thesis.

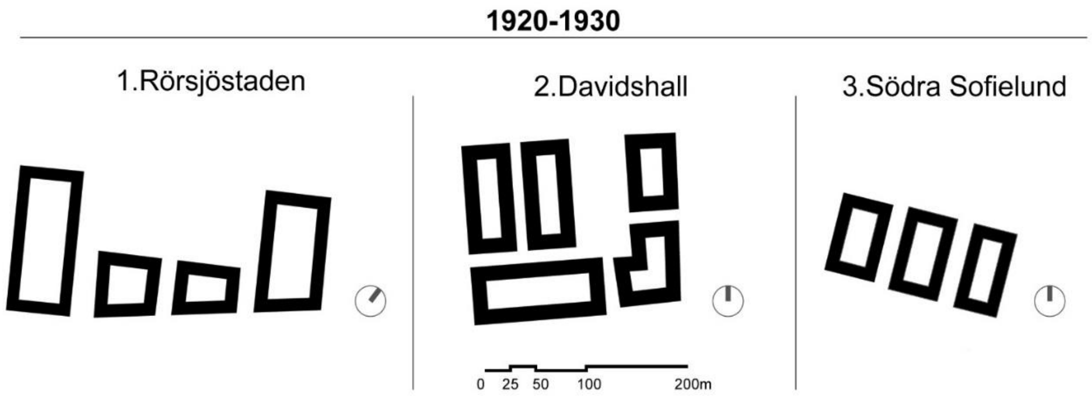


Figure 15 Malmö courtyard block examples from 1920-1930

Buildings belonging to the period 1920-1930 (*Figure 15)*, are mainly four-story structures with red brick facades and pitched roofs. Closed four-side courtyards are prevalent and it is not common to see open types of courtyards. The minimum yard dimension observed is 20 m, but in these cases the other dimension can reach 100 m. What seems to be the most common width size is 40-50m. When it comes to proportions, 1:1 types are present but not very usual. What dominates more are elongated rectangle shapes, specifically 1:2, 1:3, even 1:4 ratio.

During the 1940s and 1950s, construction work continued on the outskirts of the city, where new multi-family houses, typically 4 stories where built. The building elevation was not limited only to this height. On the contrary, groups of houses of eight or more floors began to occur, like in the Sorgenfri area, *Figure 16*.

Unlike during the 1920s and 1930s, it can be noted a higher variance in building typologies, like "U"- and "L"-shapes are present. There seem to be a tendency for grouping lamella typologies around a courtyard, like in the Rönneholm or Dammfri areas. The most typical courtyard dimension was concluded to be 30-40m, while the minimum and maximum size was 20m and 100m respectively. Most of the yard width-length proportions range between 1:1 and 1:2.

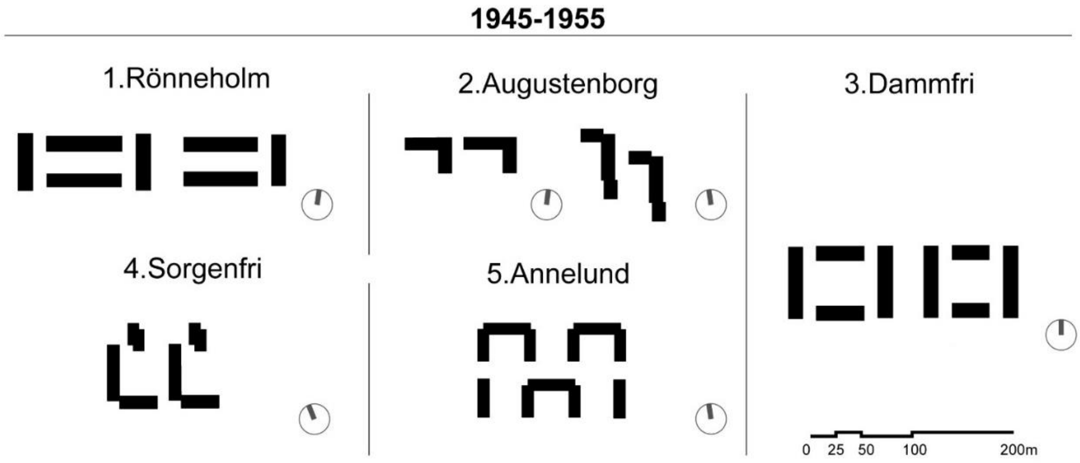


Figure 16 Malmö courtyard block examples from 1945-1955

The 1960s-1970s was a period where Sweden experienced an extensive construction boom and this was reflected in Malmö as well. Larger residential areas were built because of the "Million program" – a goal to build a million homes in ten years. This decision by the government had its impact on how the development occurred. Due to the high amount of housing needed within a short time span it was required to have a more rationalized and industrialized way of building. This led to many houses being built using prefabricated elements and with little design variance regarding building dimensions and components.

The city plans of this period were dominated by a shift between houses of three and eight or nine floors. The houses were often placed at a certain distance, 18 meters between houses on three floors, about 40 meters between eight or nine-storey houses (Länsstyrelsen Skåne Län och Malmö Kulturmiljö, 2002). The most common types of housings were the lamella type, arranged around a yard, but other typologies were present also, like the "C" type, *Figure 17*. The yard, which typically has a square shape, is bigger than before, minimum 30m and maximum dimension reaching 140 m.

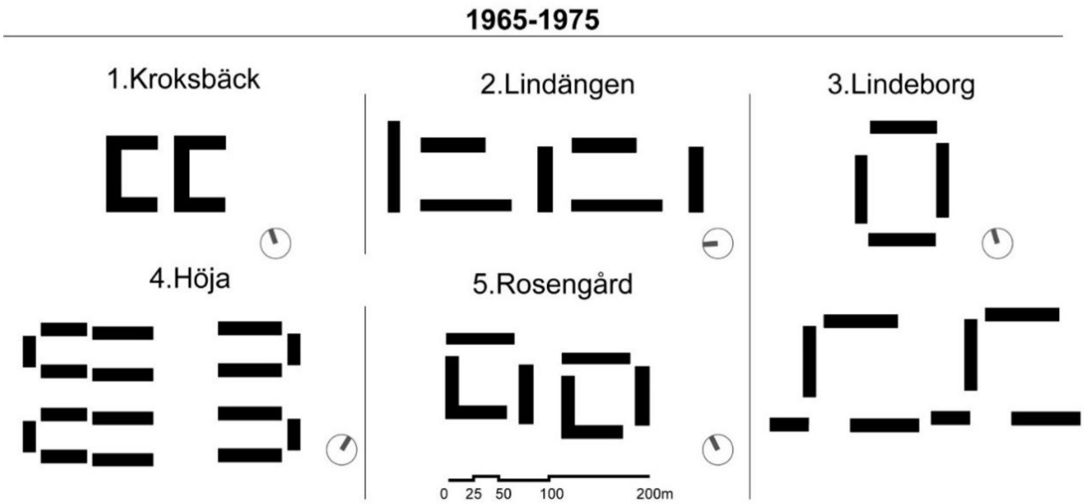


Figure 17 Malmö courtyard block examples from 1965-1975

Additionally, Västra hamnen was taken as an example of recent developments in Malmö. Just by comparing the building footprint of the previously built samples (*Figure 15, Figure 16, Figure 17*) with *Figure 18,* the difference of building scale can be clearly noted. The pressure from high land price and other factor has resulted in extensive land exploit.

What was further observed was the typology diversity; from four-side closed courtyards, to "C", "U" and "L" shapes. The courtyard dimensions have significantly decreased. In this example, four and six- storey buildings are more common. The minimum dimension of the yard is 15 m, while the maximum can barely reach 40 m

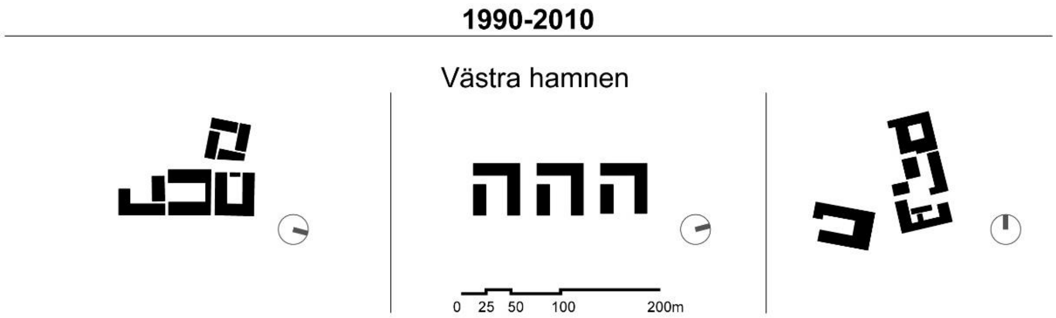


Figure 18 Malmö courtyard block examples from 1990-2010

Finally, from this study it was concluded that the most typical typologies are, "O"-type / closed courtyard, "C", "U", "L" and lamella shapes. The inner dimensions of the yard range between 20-100 m and 1:1, 1:2, 2:1 were the prevalent proportions. The minimum building height for the multi-family typologies is three stories and nine stories is the maximum encountered on these specific samples. These findings were used as the base for the theoretical model in the following phases of this study.

4.2 Phase 2: Parametric building configuration

Early in the study it was found necessary to determine the particular surface on which the VSC is to be studied for in order to achieve the finest depiction of the DF-VSC relation. Among the three adjoining façade sections: (1) entire external wall area (VSC Storey), (2) the part adjacent to the room (VSC Room) and (3) the window opening projection (VSC Window) on the same plane; the room façade area (further on abbreviated to VSC R) was selected as the most representative metric. It is also a rather easy-to-define area for early design stages.

As *Figure 19* indicates, the VSC R and the VSC W show a remarkably close relationship. Hence, considering conventional window placement, VSC R values can anytime be replaced by VSC W results when convenient. Further, there is no accurate relationship perceptible between the VSC S on the entire storey façade and DFmed indoors in any of the building typologies studied, especially, as the façade area increases, see *Figure 22.*

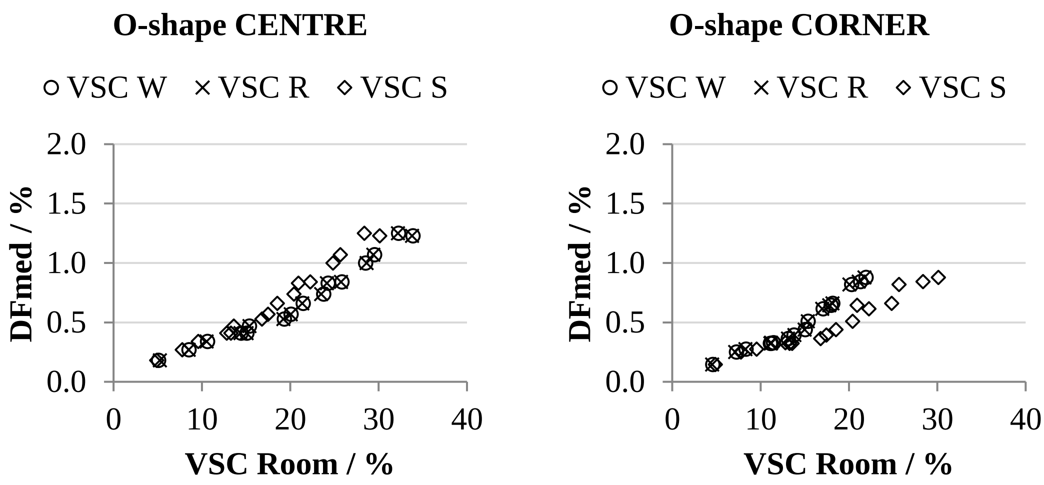


Figure 19 DFmed and average VSC on window, room and storey vertical planes for the O-shape centre and corner room position

After the Grasshopper settings were established, a simulation of the base case room without any external obstructions or buildings in context was performed. This was done to establish the maximum possible benchmark values for both the median Daylight Factor and the Vertical Sky Component on the room façade section (VSC R), which in the following studies were not to exceed DF 1.6% and VSC 39.2% respectively.

4.2.1 The impact of room placement

The base-case room was analysed from the position of the best and worst illuminated sections of the ground floor, i. e. the centre-corner or inner-outer placements. This gives the limits for the interior illumination of the room per building configuration in question. Thereafter, the shape of the building was further analysed through three courtyard ratio studies, named from the room position, 1:1, 1:2 and 2:1, as presented in *Figure 20* for O-shape context below.

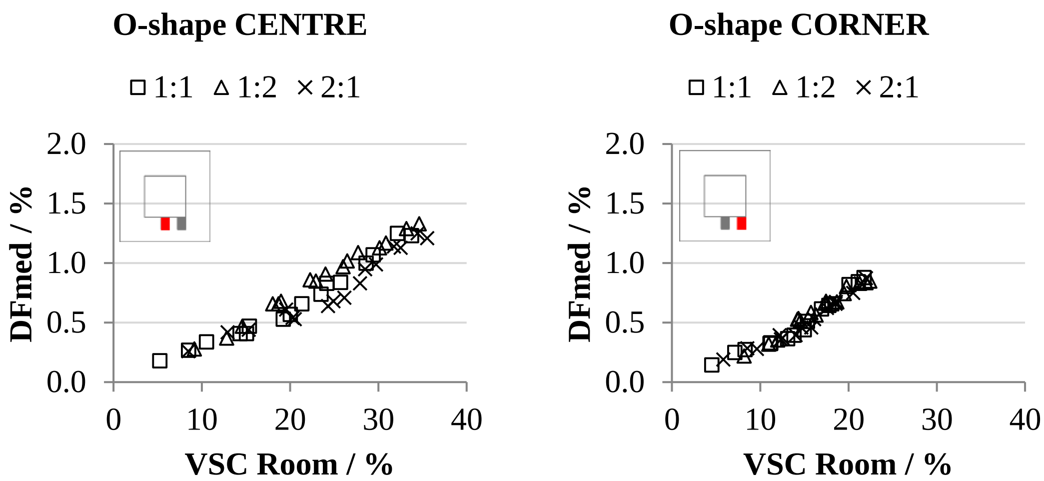


Figure 20 Relation of DFmed and VSC of the O-shape building size and courtyard ratio configuration at each of the room placements

From the graphs in *Figure 20*, representing 48 iterations per each of the room placement, it can be observed that within the building dimensions and parameters assessed in the room at the corner placement, the DFmed is below 1% in all of the cases, whereas in 73% of the centre-room cases target DFmed was not reached.

The corner room appear to be less influenced by the courtyard ratio, whereas the centre room placement is more sensitive. Due to lower obstruction angles, the 1:2 ratio represents marginally better daylight penetration indoors. However, judging from overall building performance, as all considered rooms around the 1:2 courtyard characterise the same building morphology as in 2:1, the summed trend aligns with the 1:1 yard ratio line.

A linear relation between the DFmed and VSC R can be noted from both of the graphs in *Figure 20*, where an increase in VSC R on the façade shows an increase of the DFmed indoors. The relation was further explored in *Figure 21*, where a good correlation was found with a trendline with R^2=0.93.

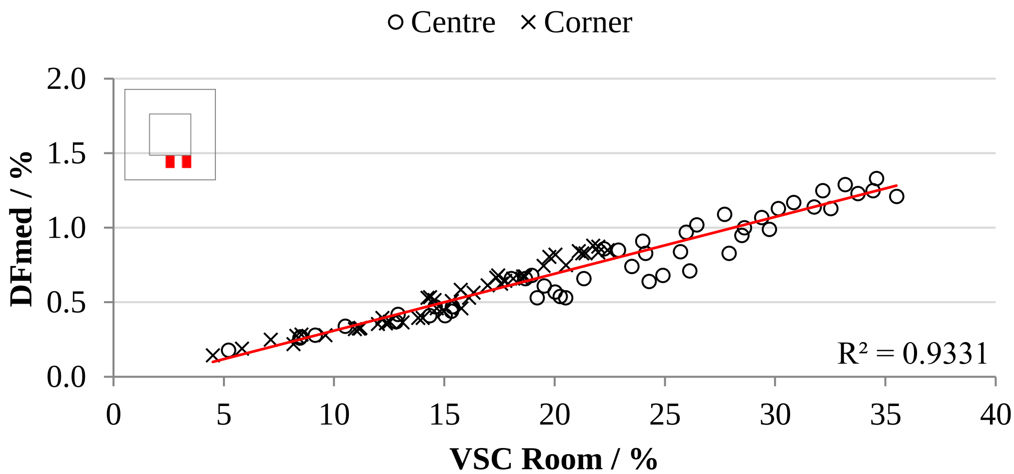


Figure 21 O-shaped function of the DFmed and VSC for a room on the ground floor

In the O-shaped building typology, the variation of the VSC R between both the middle and corner rooms per each configuration was further analysed for the courtyard 2:1 ratio due to the fact there is larger façade area exposed to the skylight. In the *Figure 22* on the X-axis there are represented each of the simulated 2:1 courtyard shapes in dimensions from 40m x 20m to 100m x 50m and building heights from 3 to 9 storeys (9 m to 27 m). On the Y-axis ΔVSC represents the range of VSC on the corresponding façade:

$$\Delta\text{VSC} = VSC\ R_{middle} - VSC\ R_{corner} \tag{10}$$

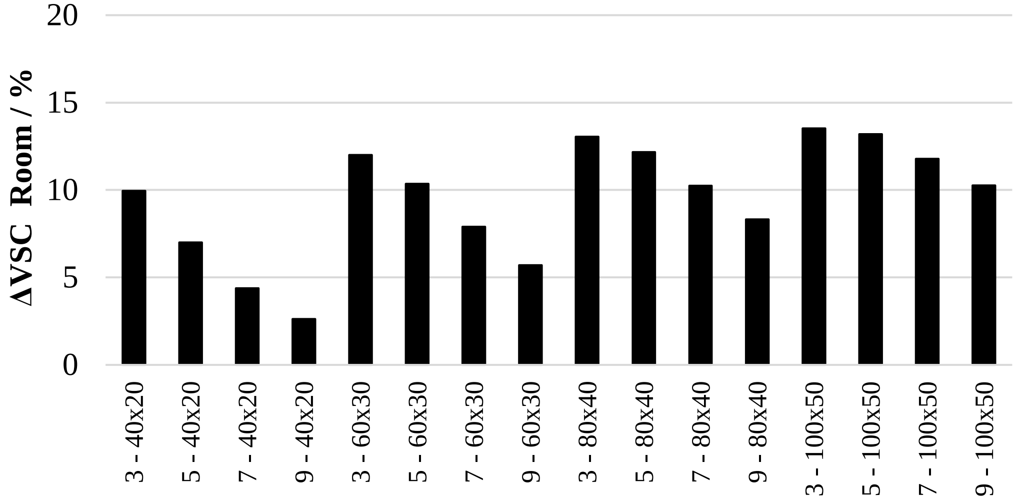


Figure 22 Range of VSC Room in entire 2:1 O-shape building ground floor façade (Note: 9 – 40x20 represent 9 stories in courtyard dimensions 40 m to 20 m from room positioning)

From *Figure 22* above it can be concluded that even in low buildings where the courtyards are less spacious, the illumination on the centre and corner rooms differ significantly, thus the interior layout must be considered accordingly. The small variation in the VSC values in a higher building context is due to already low illumination levels.

4.2.2 Combined results

By looking at all of the cases combined, a general trendline is developed to find the target value for VSC based on DFmed 1%. It is found to be approximately 29%, see *Figure 23* below.

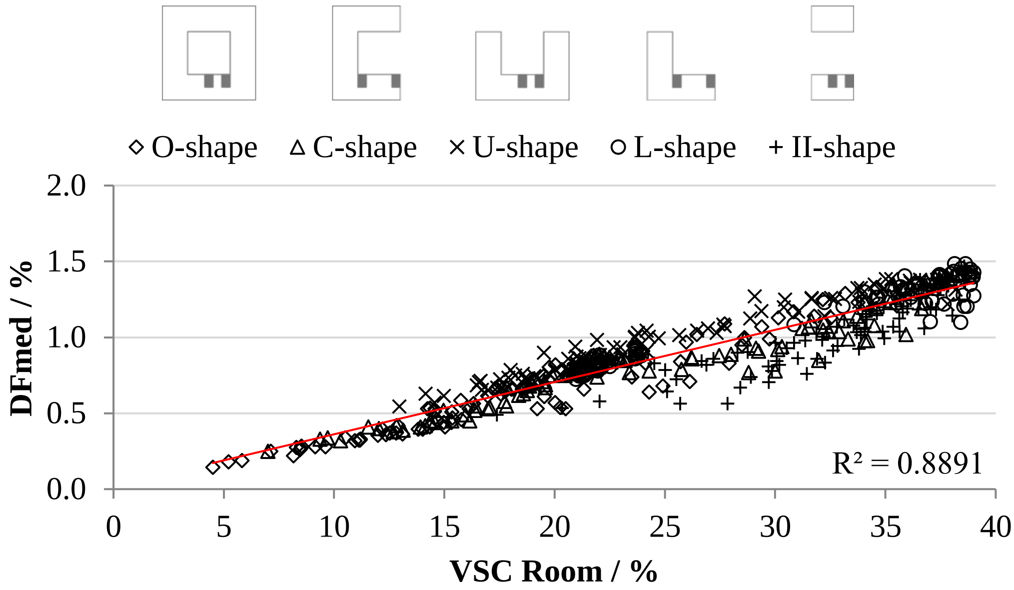


Figure 23 Correlation of the DFmed and the VSC for all of the of building configuration alternatives

As Figure 23 shows, there is a considerable range of the DFmed results for the same VSC observed. The difference is up to 0.6% between different building typologies as the VSC value increases. By looking at the VSC values more closely, U-shaped buildings yield the highest daylight factor into the room, whereas II-shaped for the same VSC generally show the lowest daylight factor.

To minimize the effect of the stochastic Monte Carlo calculation approach and estimated ±10% error (Matusiak, et al., 2015), simulated outputs were discussed on the basis of formed trendlines. The same as for O-shape results in *Figure 21*, a total of 96 simulation outputs per each building morphology were to form a trendline to visualise the DFmed and VSC function (*Figure 23*). U-shaped and C-shaped typologies were combined into one trendline to represent the whole building context.

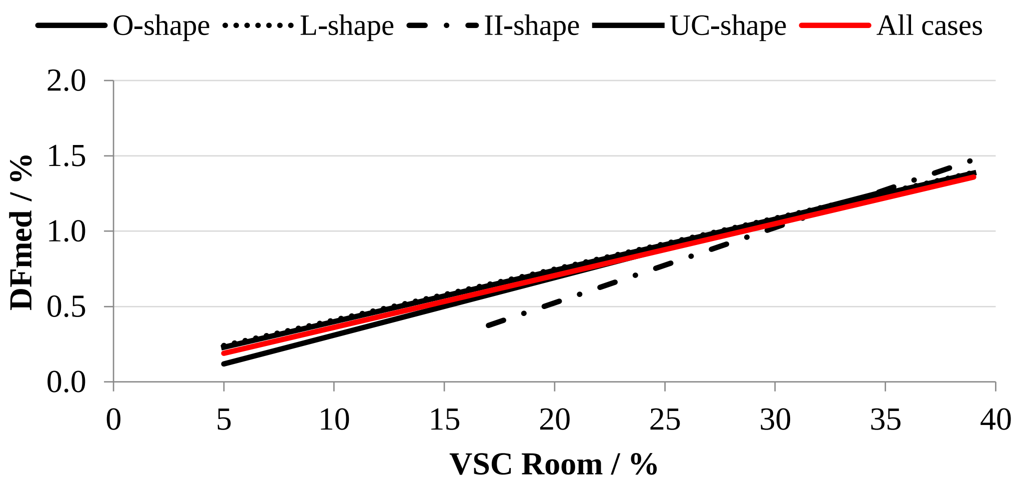


Figure 24 Trendlines representing each building typology and various VSC-DFmed relations (ρ_g 0.2)

Table 8 Changes in threshold VSC for DFmed 1% by building shape

	L-shape	UC-shape	O-shape	II-shape	All cases
VSC threshold	27.5%	27.5%	28.0%	29.5%	28.5%

From *Figure 24* it can be noted that despite the steady linear growth, the same VSC values per different building morphology do not provide an identical daylight factor indoors.

The UC-shape trendline show the results of both U- and C-shape typology simulations, which essentially represent the different room placements in the same building.

VSC R threshold values for DF median of 1% per different building shapes are shown in the *Table 8.* As it can be noted, from both the graph and the table, the deviation of target VSC R value of different building shapes and the general trendline, which was obtained by combining all the simulated results, are within minor 2% range. Thus, the choice of methodology was affirmed.

As the O-shape trendline falls the closest to the general All-cases function, it was also used to observe the impact of GFR and room depth on the DFmedian.

The L- and UC-shape appear to be slightly more favourable in comparison to other building forms in terms of interior illumination, whereas similar VSC values on II-shape context would provide the lowest DF indoors up until VSC reaches 33%.

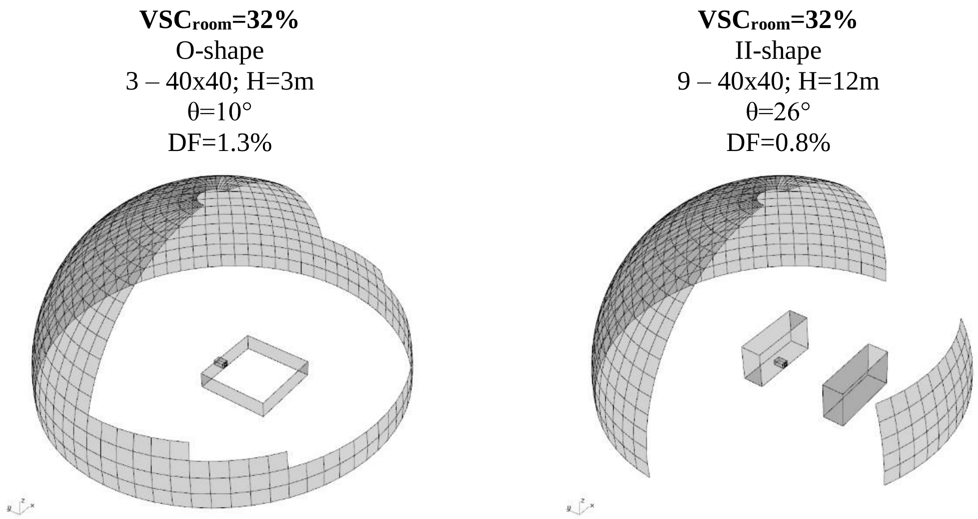


Figure 25 Impact of the visible sky zone on DFmed indoors. Note: The grey mesh from the half hemisphere represents the obstructed view from the reference point.

Starting from an enclosed O-shape building, adjoining rooms in courtyards with one or two sides open are more daylit due them having a larger view of the sky (higher sky exposure), considering the same courtyard ratio and building height. In varied heights but with the same VSC, buildings with two sides open might still be expected to receive more daylight than C- or U-shaped, especially O-shaped. However, as Hopkinson, Petherbridge and Longmore (1966) already recognized, and *Figure 24* proves – the L-shape and II-shape are very different building typologies, which is due to varying obstruction angles and which exact patch of sky is visible from the room. The most useful illumination is coming from normal to the window. The reference to Lambert's cosine law of illumination combined with the luminance distribution of the CIE standard overcast sky should be regarded when comparing other morphologies. See *Figure 25* for an example of the same VSC_{room} value in two different building contexts yielding different obstruction angles and, hence, different visible sky zones.

4.2.3 The impact of ground reflectance

All the variations of the five studied building typologies were also analysed based on the effect of increased ground reflectance, while all the other parameters were kept constant.

As expected, by improving only the ground reflectance, the ERC of the DF is increased, hence for the same VSC of room façade illuminance, there is more reflected light to interior, and by increasing the skylight availability the difference between ρ_g 0.2 and ρ_g 0.3 grows steadily, *Figure 26,* Subsequently, the threshold VSC is lowered by 3% compared to the typical ρ_g of 0.2, *Table 9.*

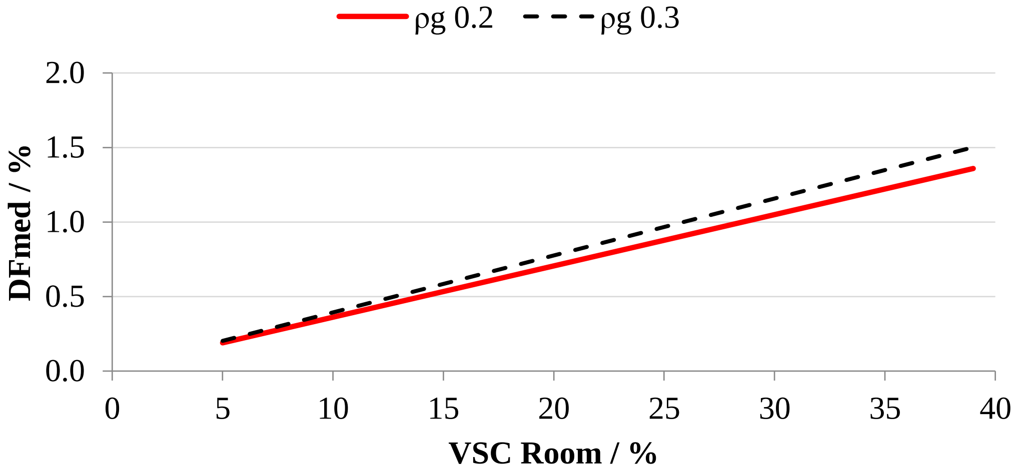


Figure 26 Correlation of the DFmed and the VSC for all of the of building configuration alternatives by increased ground reflectance

Table 9 Changes in threshold VSC for DFmed 1% by increased ground reflectance

	ρ_g 0.2	ρ_g 0.3
VSC threshold	29%	26%

4.3 Phase 3: The impact of the Glazing-to floor-ratio

This section presents the impact of different glazing-to-floor ratios to the VSC-DF correlation. From the second phase it was concluded that almost all the typologies, except "II"-type follow approximately the same trendline and if we refer to *Table* 8, "O"-type is the one which crosses the DF threshold almost at the same VSC coordinate as the overall trendline. Considering this, only the closed courtyard was taken as a reference for this part of the study.

The following figure presents the outcome of changing the glazing area from the base case W0 - type of window *(Figure 14)* to a maximum WWR of 87 %, corresponding to 0.34 glazing-to- floor ratio.

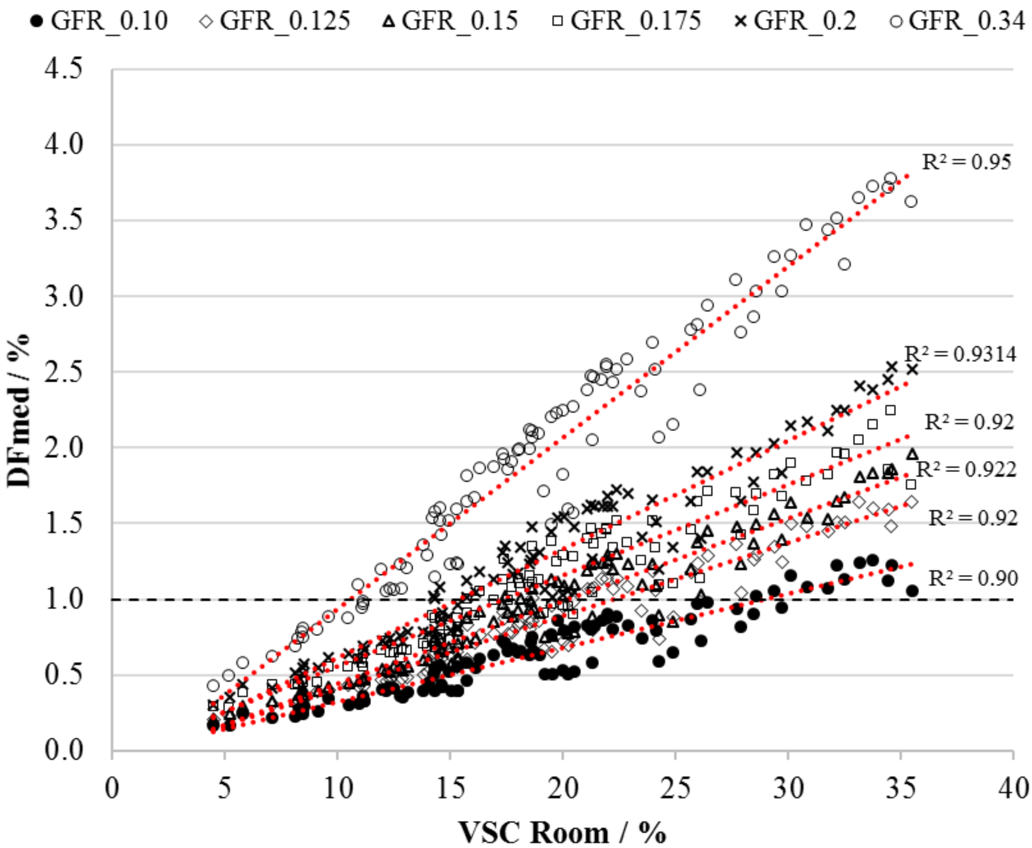


Figure 27 GFR impact on VSC-DF relation in O-shape building context

Figure 27 shows the linear correlation of VSC-DF is still present as in the previous phase and as expected increasing the glazing area gave better results on the indoor illuminance level. For each of the cases the VSC upper limit when DF median reaches 1% is summarized in *Table 10* below.

Table 10 Changes in threshold VSC for DFmed 1% by increase of GFR

	GFR 0.1	GFR 0.125	GFR 0.15	GFR 0.175	GFR 0.2	GFR 0.34
VSC threshold	29%	22-23%	20-21%	17%	15%	10%

It can be observed that the VSC threshold does not decrease constantly, even though the GFR increment happens in equal steps and the additional glazing area is roughly the same.

The biggest relative discrepancy in the VSC outset happens when GFR is changed from 0.1 to 0.125. In this case the difference is 6-7%, while for the rest of the options a change of 2-3% is noted. The lowest threshold for the most optimistic case happens at a VSC of 15%, considering a realistic upper limit of 0.2 GRF in residential buildings. If one would consider almost a fully glazed option, even though that is not common in residential typology, the required indoor illumination can be reached for vertical illumination of more than 10%. Even when applying the maximum glazing area to the selected room, it resulted that 16% of the O-type courtyard geometry iterations could not reach the DF median of 1%, see *Table 11*.

Moreover, the table below shows a statistical overview of the amount of the cases that reach the DF requirement. The same effect is reflected on the indoor daylight level, meaning the improvement for every GFR step does not occur constantly or it does not follow any certain pattern.

Table 11 Statistical overview of GFR impact on DFmed

	Unit	**O-shape**					
GFR	-	0.1	0.125	0.15	0.175	0.2	0.34
Cases DFmed ≥1%	-	12	32	39	51	63	81
% to all cases	%	13	33	41	53	66	84
Improvement*	%		21	7	13	13	19

** % of additional cases that reach DF of 1% compared to the previous GFR*

4.4 Phase 4: The impact of room depth

In order to provide a more comprehensive analysis, a parametric study on the room depth was conducted. Initially, it was decided that a room depth of 6 m could be the maximum dimension for a residential building, but from the first study it was noted that rooms as deep as 8m were present in some of the selected samples. On the other hand, rooms of 4 m depth were common. Therefore, it was decided to study a range of room depths from 4 m to 8 m. With the same reasoning as in the previous phase only the “O-type” was regarded even for this final investigation step. Please note that he window size W0 was used for all cases, which corresponds to a 10% GFR for the 6 m deep room.

Figure 28 shows, changing the room depth by 1 m steps of increment will not yield the same effect on DF for each of the enlargement steps. As anticipated, the least deep room had a better performance, where 16% of VSC can potentially yield the desired DFmedian of 1%. Moreover, the trendline from the simulation results corresponding to the 7 m and 8 m deep room did not intersect with the horizontal line representing the DF requirement. This was a confirmation that a space which has a GFR lower than 0.1 cannot reach the target value of indoor illumination.

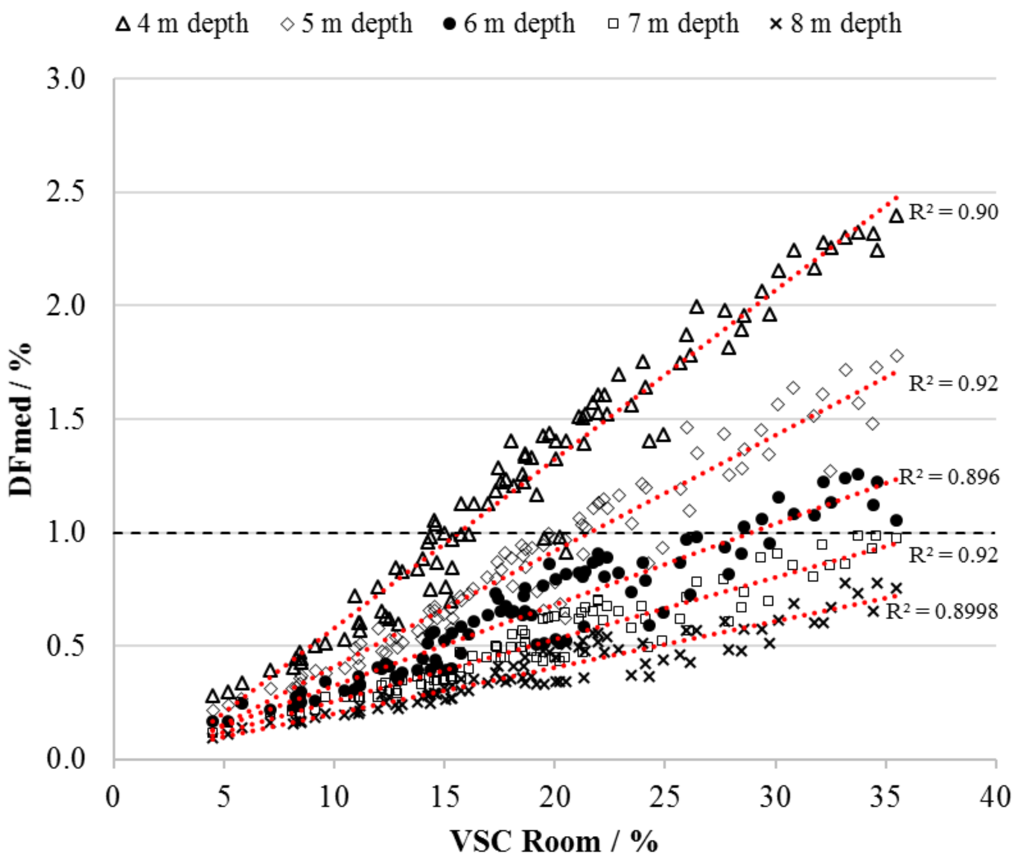


Figure 28 Room depth impact on VSC-DF relation in O-shape building context

As per *Table 12*, when the outcome of this investigation is compared to the results of the third phase it can be marked that for the same GFR a different VSC benchmark is needed. For instance, a 4 m deep room with a GFR of 0.15 demands a VSC of 16 %, while a 6 m deep room with a GFR of 0.15 requires a VSC of 20-21%.

In conclusion, the VSC threshold is lower for a less deep room compared to a deeper room given that the glazing-to-floor ratio is equal for both of the cases.

Table 12 VSC thresholds for different room depths and for equal window size.

Room depth	4 m	5 m	6 m	7 m	8 m
GFR*	0.15	0.12	0.1	0.085	0.075
VSC threshold	16%	21-22%	29%	-	-

**The glazing area is fixed at 2.4 m^2*

5 Conclusions

A deeper understanding of the relation between Vertical Sky Component and Daylight Factor was the fundamental reason to develop this thesis. The complexity of this relationship has been studied before and revealed itself again through the repetitive simulation processes, gradually forming an understanding of the source and amplitude of the influencing factors.

The fundamental aim of this study was to vary external geometries while keeping the indoor conditions constant. Five typical urban block buildings were studied, and a standard room was designed based on typical dimensions and optical properties without any additional external or internal obstructions. The main study was later advanced by assessing the impact of higher ground reflectance and varying both the window size and room depth in the O-shaped building context.

Overall, the research questions were answered: the relation between VSC and DF was confirmed, where a higher VSC usually results in a more illuminated interior space. The influence of building form was analysed, where the favourable typology was found to be the L-shape. However, overall the typology was found to have a minor significance regarding the target VSC to reach a median DF of 1%. The building shape is more important, when the daylight illumination on the façade is low i.e. when the VSC is low

Target VSC threshold values for presumably good daylight illuminance indoors were established based on the general trendline formed from 480 simulation results in total.

The proposed threshold values based on the standard room are classified in ranges of difficult, possible and good predicted daylight conditions corresponding to VSC values of ≤ 15%; 15 – 29% and ≥ 29% accordingly. The threshold VSC values are aimed to reach a median daylight factor of 1% in the adjoining room.

Recommendations for application suggest avoiding to locate living rooms and kitchens where VSC is less than 15%; where VSC is between 15% and 29% designers should avoid locating kitchens; where VSC > 29% all room types can be located. Usually lower requirements for daylight and sunlight are needed in living rooms, studies and dining rooms, as specified in BREEAM requirements, therefore these room types are recommended to be placed with restricted daylight access. Where the possibility to provide good natural light is problematic, storage spaces etc. may be placed.

The developed guideline is presented in a form of three interrelated graphs that allow a designer to assess the impact of changing the glazing-to-floor ratio or the particular room depth, hence it has both limitations and potential to influence the daylight design.

6 Discussion

The findings of this thesis may serve as a guide for architects, urban planners, designers and authorities to better understand and use the Vertical Sky Component, (VSC) as a daylight describing metric. However, due to the many parameters to be considered, the proposed threshold values should not be treated strictly but serve as a general guideline.

General findings

The daylight factor (DF) is sensitive to both the incidence angle and surface inter-reflections whereas the VSC regards only the direct skylight which can be limited by external obstructions. Due to the same reasons, similar VSC values at a façade of different building shapes and size would most likely provide different illuminance distribution in the room.

The closing guideline of three linked graphs present the impact of changing one parameter of the standard room – window size or room depth; and the impact of the ground reflectance in front of the window at the bottom floor. According to the results it was found that decreasing the room depth has larger impact on the daylight distribution in the room than increasing the window area. Nevertheless, it is understood that designers often has to consider many other factors before changing one or another daylight-influencing parameter, such as energy performance or room function.

Reference VSC threshold values

Considering that BRE established the VSC thresholds based on average DF of 2%, the values cannot not be directly compared to median DF, and conversion factor must be applied. As previously noted from a small study under our research, median DF corresponds to the same illuminance as approximately 50% of the average DF value. *Table 13* presents a comparison of the VSC threshold values as used by various institutions based on different target DF metrics. Hereby it can be noted that the mathematical DF metric conversion can be applied when threshold values of BRE and this thesis are compared, as the target threshold values for which the daylight conditions in the room can be predicted as good and satisfying, are nearly the same.

Table 13 Target VSC value comparison

	BRE: Average DF 2%	BAU: (DFavg ≈ 1.5x DFmed)	Our proposal based on the standard room: Median DF 1%
Good	> 27%	> 20%	> 29%
Possible	27% < x < 15%	20% < x < 10%	**?**
Difficult	15% < x < 5%	10% < x < 5%	**?**
Impossible	< 5%	< 5%	< 15%

On the other hand, the bottom thresholds are not similar. Our bottom threshold value is significantly higher than the BRE-guidelines. Further background of the BRE study has not been accessed. Therefore, and also due to somewhat unclear methodology and some unspecified other influencing factors, many previous studies are actually not directly comparable to our study. One should also consider that the bottom threshold value of this study is a result of a rather a safe scenario, hence the value is a conservative one.

Potential of the findings

Design tools that include simple equations and diagrams by BRE and Tregenza & Wilson (2011) were examined and evaluated against the simulated results of this study.

Since the only variables were building context: form, width and height; the Internally Reflected Component of the DF under the main study was assumed to be constant. Fluctuations and particular the ratio between the Sky Component and the Externally Reflected Component were not analysed in detail. However, variations in DF in the room appeared to be mainly influenced by the height of the building, hence greater impact from SC than ERC.

Nevertheless, due to the considerable impact of the SC, the relation is not directly proportional to obstruction angle only, as Tregenza & Wilson (2011) formula $VDF_w \approx \frac{\theta}{2}$ and *Figure 6* imply. The *Figure 29* presents the relation between the VSC and obstruction angle for three of the simulated settings in comparison with the calculated values. As the results show, the VSC estimation based on known obstruction angle is a rather ambiguous method even for evaluating simple geometries.

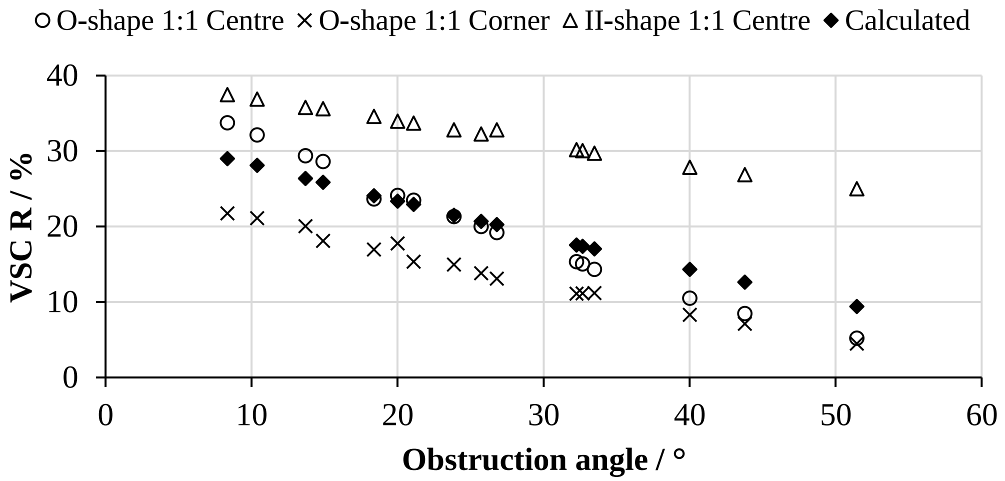


Figure 29 O-shape result alignment with VDF rule-of-thumb by Tregenza & Wilson

Reliability of the results

Simulation tools are a powerful force to accelerate information processing, in this case Radiance though the Grasshopper interface. On the other hand, the results are often hard to judge due to heavy theoretical and mathematical background. The accuracy of the individual DF simulation results was based on the stochastic Monte Carlo calculation method that is accounted for ±10% result margin, often too optimistic (Dogan, Reinhart & Michalatos, 2004). Therefore, the simulation output was to be studied in a high number of cases to increase both the accuracy and reliability of the results. As the study was based on theoretical building models, to validate the results, an evaluation against the on-site measurements ought to be made.

The results of enclosed courtyard (O-shape) were consistent with Du & Sharples (2009) research outcomes.

Limitations and future work

The simulated daylight factor is based on an overcast sky model hence all received light has to be diffused, and in a symmetrical building all the rooms around the courtyard allegedly would have the same simulated DF values. This is a crucial simplification to be considered by designers when assessing the performance of a space since the direct radiation is removed from the internal daylight distribution. In reality, the effect of varying sky types from cloudy to clear, and the solar path must be taken into account to avoid excessive heat gains and glare issues through south-faced windows. Standards specify that glazing-to-wall ratio should not fall behind 10%, but changes in window area must be evaluated from both a daylight and an energy perspective.

Another limitation of the research is its focus on residential buildings. The change in function would require adjustments of the standard room and would thus deliver different results.

The studied range of obstruction angles 4° – 51° was an optimal selection within the scope of the thesis. However, to obtain a better overview of the complete cityscape, analysed heights should be increased, and an additional typology of urban canyon representing streets widths of 10-12 m and increased obstruction angles should be further analysed, and the trendline compared with the currently observed building typologies.

For high obstruction angles – which typically occur when the courtyard size is small, and/or the building height is considerable – different layouts for the corner spaces compared to those positioned in the centre should be considered due to the rather different VSC values that occur for the different positions of the room. As observed this is often the most critical parameter for optimal natural illumination indoors.

The effect of obstructions above the window, such as balconies or fixed shading, was not considered during this work. However, any obstruction that shades the top part of the sky as seen from the window will significantly reduce the direct skylight and so both VSC and DF. Therefore, it is not advised to place windows under large balconies. Placement of balconies is a choice that the architect can control better, given a certain detailed development plan, while the overall building typology and distance to and height of neighbouring buildings is given by the plan. This was one reason why we omitted balconies from our study. It is safe to say that the presented or established VSC threshold values are not applicable to such cases. Therefore, it would be beneficial to analyse VSC under an overhang / balcony parametrically changing the depth and width of it.

A central assumption was the thickness of the external wall at 0.40 m. It created an overhang at 15° angle from glazing plane in the middle of the wall to the window recess, which was included in the DF computation by design. The potential impact of varied window offset from the external façade is therefore not estimated.

Also, it would be useful for urban planners and beneficial for everyone to observe the outdoor spaces in terms of available sunlight hours and establish a guideline to be used in the building code. All to assure that every human being is feeling well in the built environment both indoors and outdoors.

Finally, in order to validate this thesis findings and other VSC thresholds proposals, field measurements can be initiated in the future.

7 Guideline application

This chapter is a summary of all the outcomes from this investigation wrapped up as a set of guidelines. Based on *Figure 30* some instructions are given for the potential users:

Prior to using the guide, a VSC simulation, which can be limited to the ground floor is necessary. Afterwards three scenarios are possible:

1. If the VSC is more than 29%, then there is a very good possibility to reach the indoor DF med of 1%.
2. If the VSC outcome is a value between 15% - 29% (in the example below it is 22%), then for a room 6m deep with 0.1 GFR it may be difficult to reach the target daylight level, but it can be possible with some adjustments. For this scenario the last two graphs can be handy to search for some solutions in order to fulfil the requirement. If the desired room depth is going to be 6 m, then a GFR of at least 0.125 is need. If increasing the glazing area is not possible due to some reasons, changing the room depth can be another alternative. Specifically a room with the maximum depth of 5 m can be regarded. Certainly, approximation can be made and other options can we derived from the graphs.
3. Lastly, according to this study’s findings, if VSC turns out to be less than 15 % it is advised to reconsider the geometry, as it is probably unlikely to achieve the required indoor daylight factor.

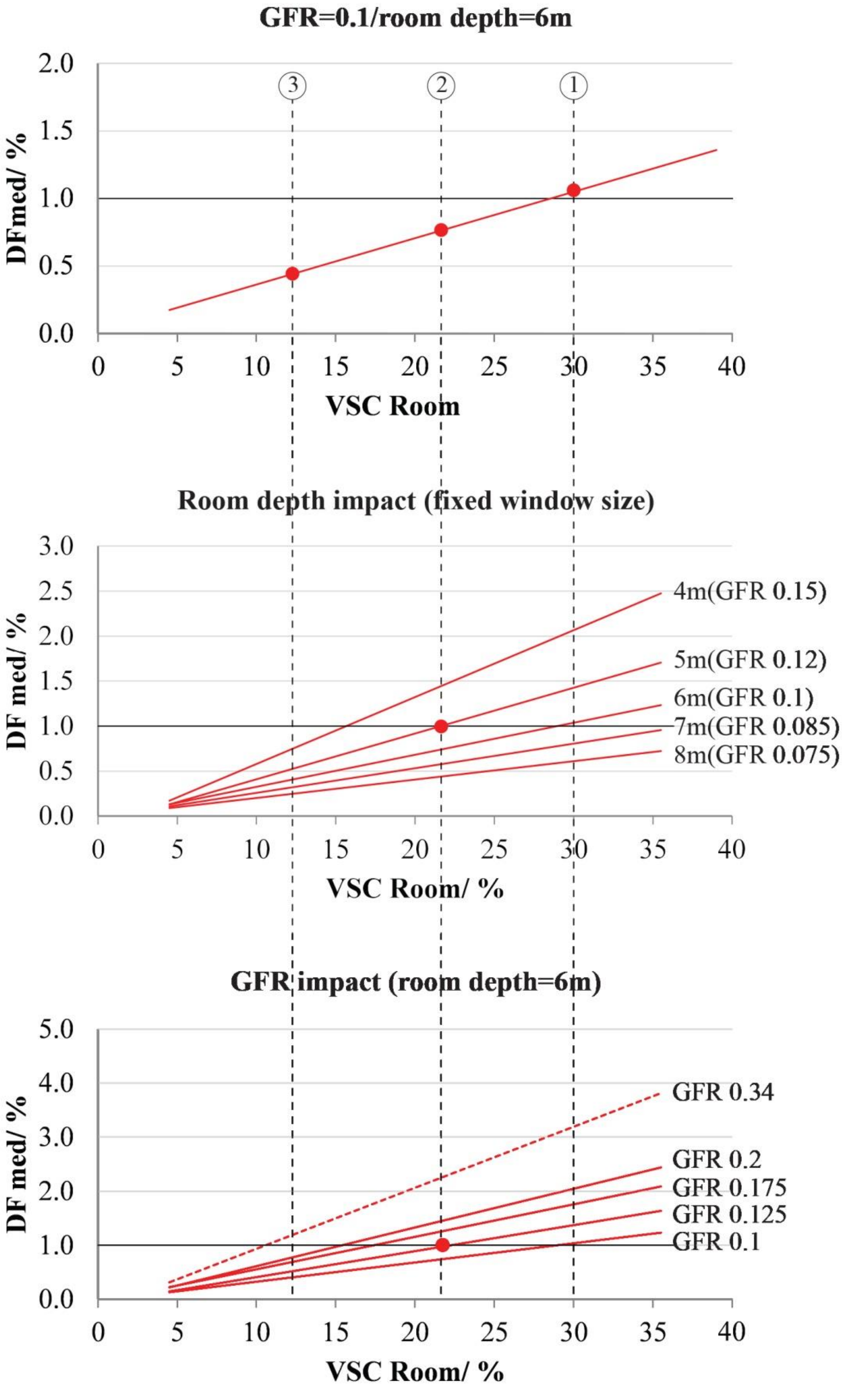


Figure 30 Guideline proposal based on VSC-DF relationship

8 Summary

The current trends in the building industry are aiming towards maximizing the plot ratio resulting in denser cities and high-rise buildings, where space availability is diminishing constantly. Along with urbanization pressure, the growing national and EU energy-efficiency demands has implicated the daylight performance. Many researchers have been studying the importance of solar insolation and its social and health benefits but also the potential to reduce the energy demand. Thus, achieving a balance between energy and daylight interest becomes more essential, especially if more attention is given on early stages of design.

The focus regarding daylight in Sweden has been on the building level and there is no daylight regulation in early planning phase which often causes potential problems in the successive stages. Moreover, the current standards part of the Swedish building code or Miljöbyggnad certification system are often associated with a lot of application limitations and uncertainties, beside the large amount of time required for calculations or simulations.

All these factors suggest that a new method is needed to facilitate the process of daylight estimation during early design phase, while potentially save considerable time and resources. Therefore a simple conceptual metric such as Vertical Sky Component is introduced and its relation with Daylight Factor is investigated with the purpose to develop a set of guidelines for architects and urban planners.

Initially, it was necessary to get an overview of building block configuration in Malmo, as a basis to define some theoretical models to carry out this study. Afterwards the investigation was basically divided in three parts. The core study consisted of using Grasshopper and Honeybee tool to perform a parametric study under CIE overcast sky condition in five typology representations, specifically “O”, “C”, “U”, “L”-type and lamella shape. The courtyard size, proportion and building height were varied, while measuring the indoor median DF in two different room placements on the ground floor level and the VSC on the room façade. Additionally, two other complement studies were applied to O-shaped courtyard, where glazing area and room depth and were further inspected.

The core study demonstrated that there is clearly a linear relation between the indoor and the façade daylight level. Considering the trendline of 480 simulated cases, the VSC threshold value to achieve the indoor target DF of 1% resulted to be 29%.

In general 1:2 yard ratio represented slightly better daylight penetration indoors, due to lower obstruction angle. For closed courtyards and those having only side open, it was observed that 1:1 proportion gave better indoor daylight than 2:1 ratio, even though the latter are more spacious, and the obstruction angle is the same as 1:1 courtyards. The proximity of the lateral walls on 1:1 courtyard proportion can be an explanation of more interreflected light, thus better daylight performance.

It was noted that the same VSC value per different building typology did not provide identical daylight illuminance indoors, mainly because of the interreflection contribution and exact patches of visible sky from the room. The U-shape building allowed the most daylight penetration into the room, whereas II-shape at the same VSC generally showed the lowest DF med.

The results from the GFR study showed that the VSC threshold did not decrease constantly, even though the GFR increment was in equal steps and the additional glazing area was roughly the same. The lowest threshold for the most optimistic case happened at a VSC of 15%, considering a realistic upper limit of 0.2 GRF in residential buildings.

The last supplemental analysis on room depth revealed that extending the room by 1 m of increment will not yield the same effect on DF for each of the enlargement steps. As anticipated, the narrowest room had a better performance, where 16% of VSC can potentially reach for indoor daylight level. Moreover, a confirmation that a space which has a GFR lower than 0.1 cannot reach the target value of indoor illumination was obtained. When comparing the outcome of the last two analysis, lower VSC threshold is needed for a smaller room compared to a deeper room with bigger window, given that the glazing-to-floor ratio is equal for both of the cases.

Finally, all the results of this research work are presented in a form of three interrelated graphs and some instructions are given for the potential users.

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A Appendix: Radiance parameters

(Larson & Shakespeare, 2003) and (Ward, n.d.) were used as a source information to understand the concepts of the radiance parameters complimented by (Dubois, 2001) sensitivity analysis to define the parameters used on this study.

According to the Dubois' study, the options which had the most dramatic impact on rendering time were the ambient accuracy and ambient resolution (-aa and -ar). The conclusion from her analysis was that the greatest precision was obtained by combining high accuracy settings (see Table 14 below, from the same study).

Table 14: Rendering options settings for medium and high accuracy (from Ward Larson & Shakespeare, 1998 and Ward, 1996)

Rendering option	Description*	Medium accuracy	High accuracy
-ab	Maximum number of diffuse bounces computed by the indirect calculation.	4	8
-aa	The maximum error permitted in the indirect irradiance interpolation.	0.15	0.08
-ar	Sets the ambient resolution, determining the maximum density of ambient values used in interpolation	128	512
-ad	Sets the number of ambient divisions, which is how many initial samples will be sent over the divided hemisphere.	400	2048
-as	Set the number of ambient super-samples or extra rays that will be used to sample areas in the divided hemisphere that appear to have high variance	64	512

** Extracted from (Larson & Shakespeare, 2003)*

Considering the extensive amount of the prospective simulations, it was deemed to start with (-a..) options ranging between medium and high accuracy values. The actual chosen values were based on some tested successive simulations of the same defined geometry, but also on some rule of thumbs and guidance discussed further on.

The scale over which interpolation may occur is closely related to (-aa) and (-ar), and maximum scene size and is defined by the following formula, where D_{max} stands for maximum scene dimension and S_{min} is the minimum separation for cached irradiances.

$$S_{min} = \frac{D_{max} \cdot (-aa)}{(-ar)} \text{ [m]} \qquad (4)$$

Lower (-aa) and higher –ar will lead to lower minimum separation for cashed irradiances, meaning that the interpolation will occur for smaller distances, therefore higher accuracy is expected along with slower computational time.

The (-aa) option was preset to 0.1 and the maximum scene size, which in general is the ground size, was determined. Its dimension was decided upon Mardaljevic rule of thumb, that the ground plane should be at least twice the maximum extent of the scene contents. The ground for this study was set to be four times as the maximum extent of the scene, specifically 500 m. Then (-ar) 300 was determined in order to reach a S_{min} less than 0.25 m, because for scales smaller than 0.25 m it is far less likely to impair the results (Mardaljevic, 2003).

When deciding on ambient bounces (-ab), an accurate (±10%) illuminance prediction was aimed and it usually requires four or more ambient bounces to achieve it, according to Mardaljevic. This is especially important on deep rooms, where interreflection becomes more important. As the difference on the calculated output after 4 bounces is not considerable, as some study confirm and many Swedish offices are using (-ab) 6 in their daylight simulation, it was justified to use (-ab) 6 in this study too.

Regarding ambient division parameter, it was noticed that it had a big impact on the relative error of the same consecutive trial simulations. Values between 1024 and 2048 were tested and the conclusion was that higher ambient divisions generated less deviation, as this was presumably related to the Monte Carlo calculation error of indirect illuminance, which is inversely proportional to the square root of this number. (Larson & Shakespeare, 2003) Another observation was that increasing ambient divisions resulted in lower absolute values of DF median.

Additionally, the as option was regarded as less significant compared to ambient devision, so a value of one quarter of this ad was considered.

B Appendix: Simulation results per typology

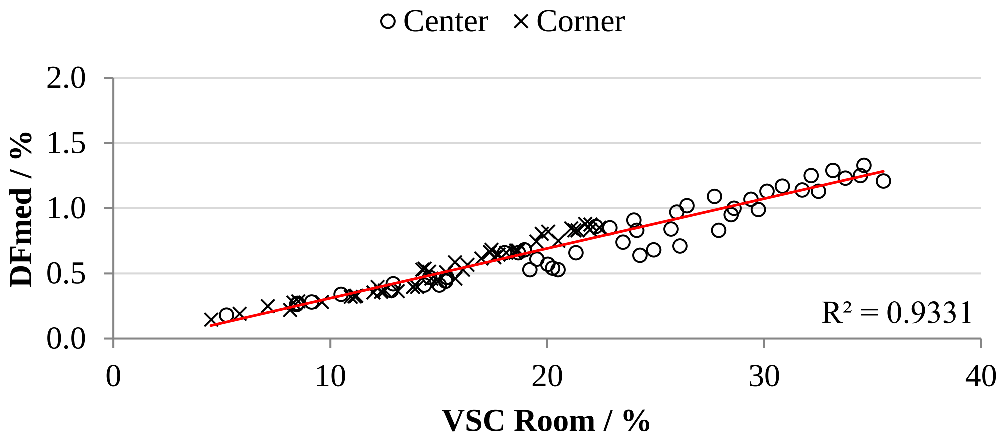

Figure 31 Phase 2: O-shape

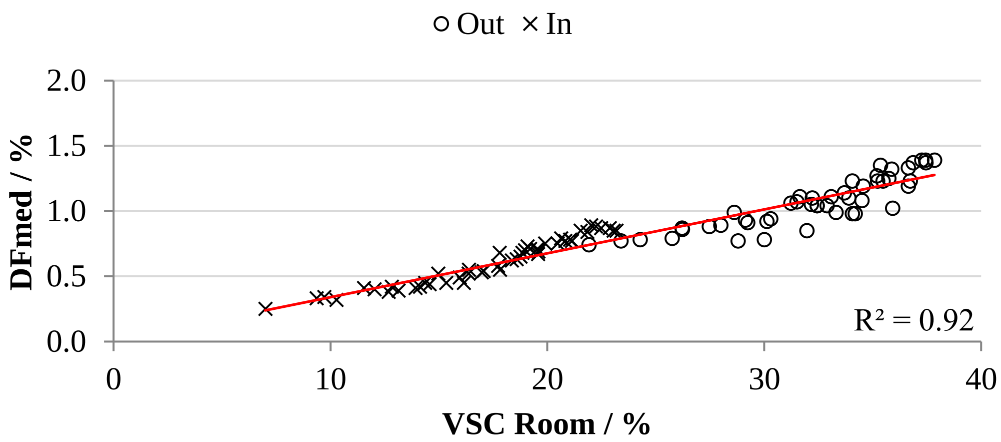

Figure 32 Phase 2: C-shape

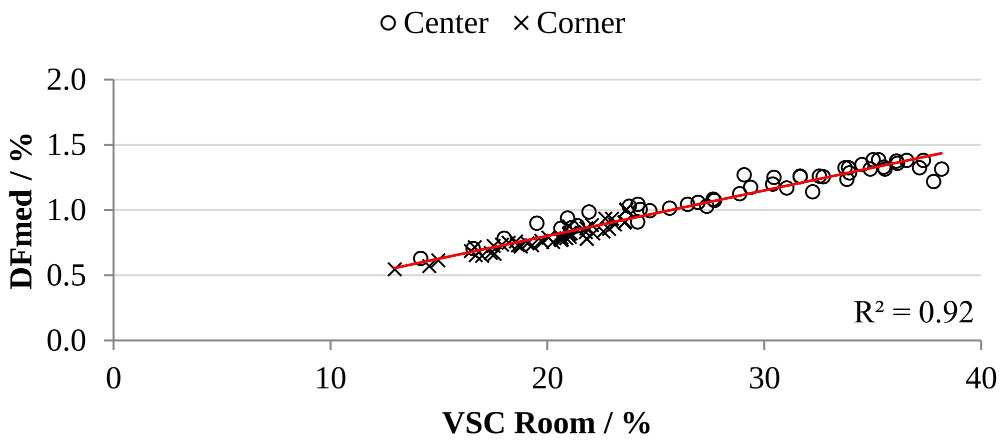

Figure 33 Phase 2: U-shape

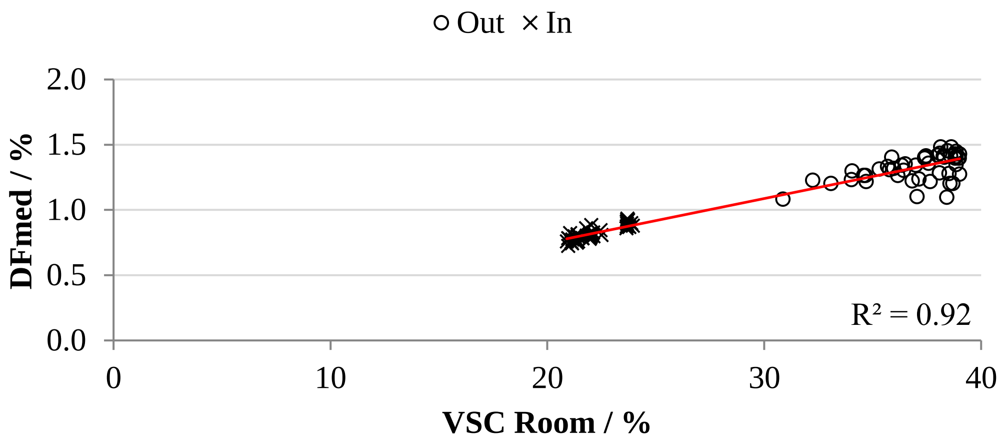

Figure 34 Phase 2: L-shape

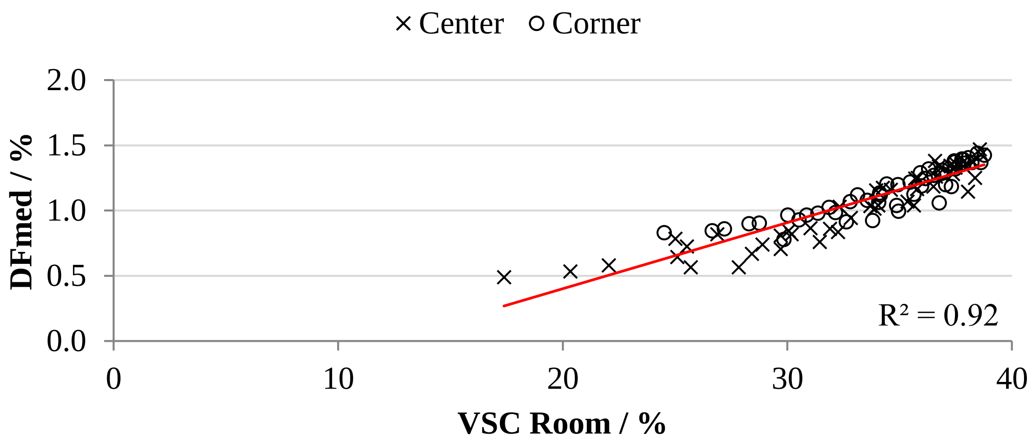

Figure 35 Phase 2: II-shape

C Appendix: VSC R range

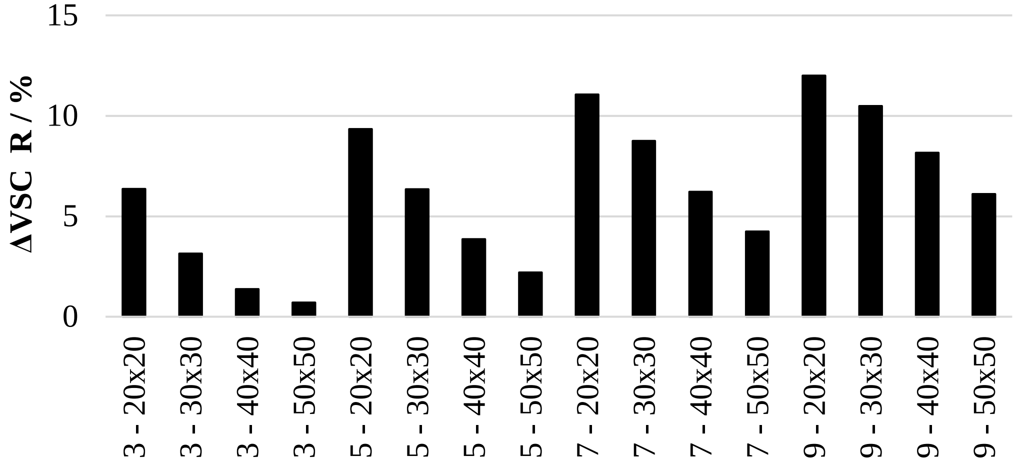

Figure 36 Phase 2: Range of VSC R in 1:1 O-shape

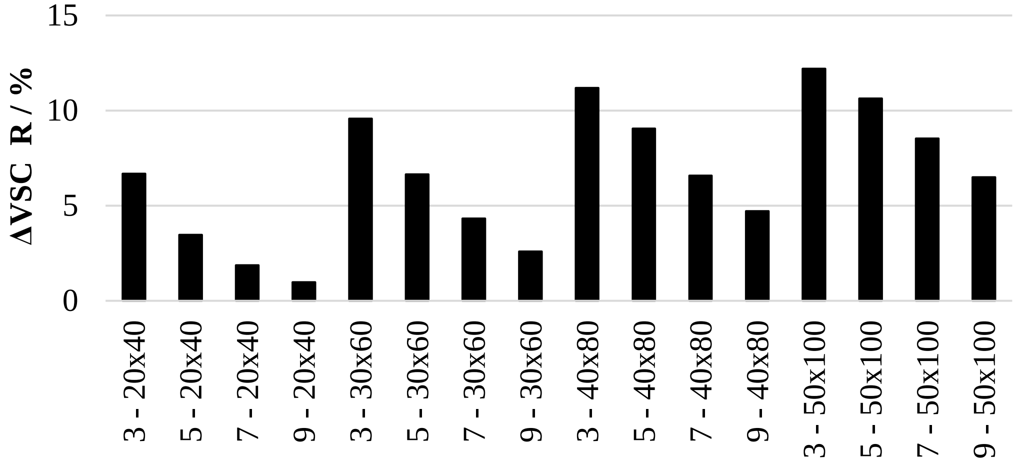

Figure 37 Phase 2: Range of VSC R in 1:2 O-shape

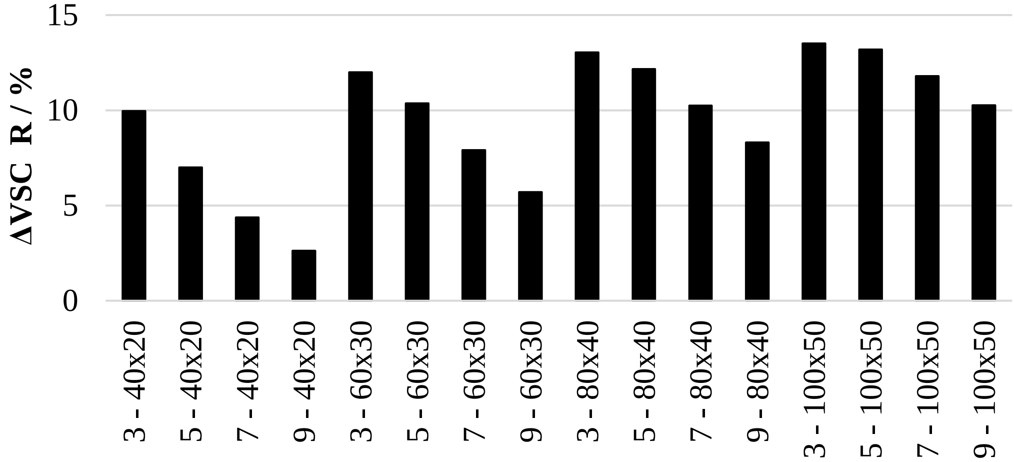

Figure 38 Range of VSC R in 2:1 O-shape

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