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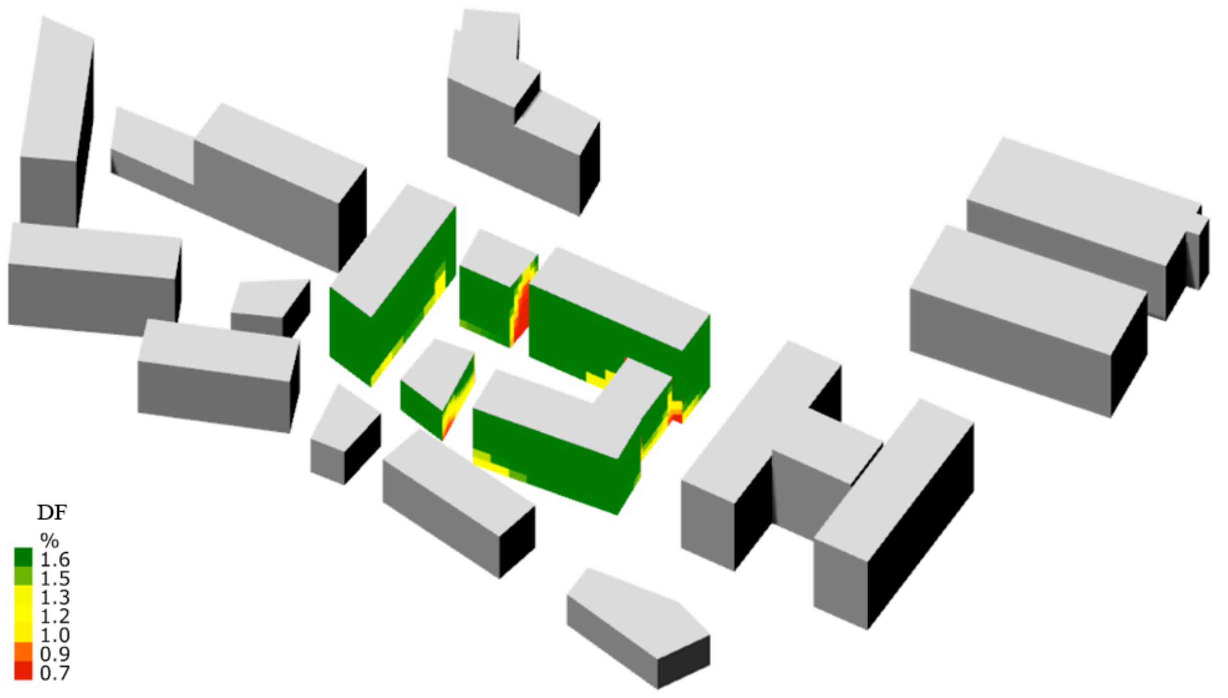

Evaluation of Sun- and Daylight Availability in Early Stages of Building Development

A Method Based on Correlations of Interior and Exterior Metrics

Master's Thesis in the Master's Programme Structural Engineering and Building Technology

EMMA JACOBSSON
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Department of Civil and Environmental Engineering
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Master's Thesis BOMX02-17-65

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Cover:
The figure shows the case study Lindholmshamnen and the result of the simulated Daylight Factor in actual values.

Department of Civil and Environmental Engineering. Gothenburg, Sweden, 2017

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ABSTRACT

It is of great importance to evaluate a building development in early stages of design, in order to fulfil current building regulations on energy performance and comfort. There are several simulation methods, which are meant to focus on early design analyses, though results are often only possible to achieve in later stages of design, due to the limitations of input data. Simulations with regard to solar heat gains and daylight calculations are incorporated into the design later on, leading to design issues which could be impossible to solve.

The purpose of this Master's thesis is therefore to develop a methodology that with simple 3D models and input data can provide reliable indications of a building's performance with regard to sun- and daylight availability, in the earlier stages of design. Additionally, the energy performance of a design is assessed through the mean value of the thermal transmittance. By implementing this type of simulation tool in the design process of city planning, it would be easier to set the prerequisites for an urban area, based on the conditions on site. This would lead to issues being revealed and solved directly. Setting reasonable visions for new building developments, which are possible to achieve, would lead to a more sustainable densification.

The choice of simulation methodology is based on an extensive literature review of the workflow of existing calculation software. Choosing the most important performance metrics, which also are possible to simulate in early evaluations of building development, led to the choice of simulation structure. An additional investigation of a correlation between the Daylight Factor and an exterior metric enabled the evaluation of daylight availability in early design stages.

The developed simulation methodology has been verified through two representative case studies, though it needs further validation in order to establish the correctness of the methodology compared to a detailed calculation. However, it provides indications that could be useful for evaluating building development and the chances for it to facilitate the design process are considered to be promising.

Key words: daylight, sunlight, thermal transmittance, U-value, energy, Rhinoceros, Grasshopper, LadyBug, HoneyBee, early stages of design, correlations, metrics, methodology.

Analys av sol- och dagsljustillgänglighet i tidiga designskeden
En metod som bygger på samband mellan interna och externa indikatorer

Examensarbete inom masterprogrammet Structural Engineering and Building Technology

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SAMMANFATTNING

Det är av stor vikt at utvärdera nya bostadsområden i tidiga designskeden för att verifiera om möjlighet finns att uppnå byggkraven för energiprestanda och termisk komfort. Det finns flertalet metoder som anses vara anpassade för denna typ av utvärdering, dock visar de sig bäst lämpade för senare steg i designprocessen där fler designparametrar är bestämda. När simuleringar för att bestämma solvärmelaster och beräkna dagsljus tas fram är det ofta för sent att lösa de problem som uppstår.

Syftet med det här examensarbetet är, baserat på ovanstående, att utveckla en metodik som med avskalad indata och geometrier kan ge pålitliga indikationer av en byggnads prestanda med avseende på sol- och dagsljustillgänglighet i tidiga designskeden. Utöver detta kompletteras metodiken med energiprestanda för de analyserade objekten genom beräknade medelvärden för termisk transmittans. Genom att implementera detta tillvägagångssätt i byggbranschen kan nödvändiga förutsättningar bestämmas baserade på förhållandena i området. Detta skulle leda till att problem identifieras tidigt och således kan bli lösta direkt. Att sätta rimliga visioner för nya utvecklingsområden som dessutom är möjliga att uppfylla skulle leda till en mer hållbar förtätning.

Valet av simuleringsmetodik är baserat på en omfattande litteraturundersökning av befintliga beräkningsmetoder. Utifrån undersökningen valdes de mest relevanta enheterna ut, vilka ansågs vara möjliga att utvärdera i tidiga utvecklingsskeden, som i sin tur ledde till den fastslagna simuleringsstrukturen. Utvärdering av dagsljustillgänglighet i tidiga skeden möjliggjordes genom en undersökning av samband mellan dagsljusfaktorn och externa indikatorer.

Den utvecklade simuleringsmetodiken har blivit verifierad i två fallstudier dock krävs vidare verifiering för att säkerställa att metodiken är tillräckligt korrekt jämfört med detaljerade beräkningar. Trots detta ger metodiken indikationer som kan vara användbara för utvärdering av exploateringsområden, där chanserna för att den ska kunna underlätta designprocessen uppskattas vara lovande.

Nyckelord: dagsljus, solljus, värmegenomgångskoefficient, U-värde, energi, Rhinoceros, Grasshopper, LadyBug, HoneyBee, tidiga designskeden, samband, indikatorer, simuleringsmetodik

Contents

Preface

This Master's thesis has been accomplished in a collaboration with Bengt Dahlgren AB and Chalmers University of Technology and carried out from January to June 2017. The project is partly based on the Master's thesis of 2016 called "Daylight in Existing Buildings" where the continuation this thesis is built upon was proposed by Max Tillberg and Anna Larsson from Bengt Dahlgren AB. The thesis work have been performed at the office of Bengt Dahlgren AB in Mölndal and at Johanneberg Science Park in Gothenburg.

We want to address our gratitude to our supervisors both at Chalmers University of Technology and Bengt Dahlgren AB, Angela Sasic Kalagasidis along with Max Tillberg and Anna Larsson. Without your supervision, guidance and supplemental ideas this thesis work would not have been possible to perform.

Finally, the background to this thesis has been based on interviews, which were possible thanks to Älvstranden Utveckling AB and White Arkitekter AB.

Göteborg Juni 2017

Emma Jacobsson och Fredrik Eriksson

Notations

CIE Overcast sky **-** the conditions of luminance changes with the altitude. The luminance is three time higher at zenith than at the horizon.

Clear sky – Less than 30 % clouds or no clouds covering the sky. The sun is visible and is brighter towards the sun than in the other parts of the sky hemisphere.

Continuous Daylight Autonomy (cDA) – Modification of the DA. The metric refers to the percentage of the floor area that exceeds a certain illuminance level for at least 50% of the time, where time steps below the illuminance threshold value also are accounted for.

Cosine weighted value – when light in a certain angle strikes a surface (vertical or horizontal), it is corrected with a cosine function which contributes to a weighted value of the intensity of light. Depending on the relation between the surface and the part of the visible sky hemisphere, the intensity becomes higher closer to zenith than the horizon.

Daylight Autonomy (DA) – the percentage of daytime that a space achieve a certain threshold value of illuminance. The term daytime is optional and could concern occupied time, daylit time or annual time.

Daylight Factor – ratio between illuminance indoors compared to available illuminane outdoors, under an overcast sky.

Energy Use Intensity (EUI) – Energy metric for measuring the intensity of energy usage per total gross area, expressed as J/m^2 (EU) or kBtu/ft^2 (US).

Illuminance [Lux] – Amount of visible light hitting a surface.

Luminance [Cd/m^2] – Visible light emitted by a surface.

Ray tracing – tracing the way of the light from an object or source. Two different sort of ray tracing exist, backward- and forward ray tracing. If tracing is performed from the source (the sun) it is called forward and vice versa for a surface.

Sky Exposure Factor (SEF) – Geometrical based metric expressing the amount of visible sky for a certain point. Section 3.2.3 contains supplementary explanation of this metric.

Sky View Factor (SVF) – the amount of sky visible in percent, from a surface or set of surfaces. The closer to zenith, the higher the value of SVF is weighted. Further explanation can be found in 3.2.2.

Solar irradiance [W/m^2] – Power emitted from the sun, falling on a surface.

Solar radiation [W] – Power emitted from the sun (without direction).

Spatial Daylight Autonomy (sDA) – the percentage of space that is daylit (above the illuminance of 300 lux) more than 50 % of the occupied hours. Used for evaluation of daylight quality.

Uniform sky - a sky dome with homogenous luminance. This means that the luminance does not change with the altitude.

Vertical sky component (VSC) – amount of sky illuminance on a vertical surface compared to illuminance of an unobstructed sky on a horizontal surface.

1 Introduction

The following chapter presents the background, purpose, delimitations and method for this thesis. The different subchapters are briefly described and give an idea of how the subject got developed into a complete Master's thesis but also how the topic was approached.

1.1 Background

With the increasing level of urbanization comes a densification of our cities, which often leads to negative consequences for the amount of daylight in buildings. This is often due to the fact that the design in early stages does not include a procedure of evaluating the levels of daylight in a building. Similar to the daylight related problem, the amount of sunlight hours from direct radiation, which is location dependent, needs to be satisfactory. The more surrounding obstructions, the more the available daylight and the amount of sunlight hours decrease. Furthermore, the solution of daylight improvement is often to increase the size of windows that leads to an increased solar heat load where excessive energy consumption might be the consequence.

In planning and design of a new area, two parties are often involved in the process, a developer and an architect[1]. When it comes to urban planning, the developer works in close collaboration with the municipality to evolve site plans and sustainability plans where the vision, requirements and goals for the new area are gathered. During the development of the site plan, the architect can assist with visualisation of the planned area in form of drawings and models. The buildings are placed and some parameters such as the footprint and the building heights are determined. During later design stages, the architect together with a contractor tries to achieve a design according to the requirements of the site plan, which often can be a challenge. The architect's possibilities are limited and can influence the choice of materials, adjustments of parameters as window areas, interior layout and if and where to place balconies[2].

When working in design processes, there are building regulations that need to be satisfied, both concerning the Daylight Factor and the direct sunlight hours. The solar heat load is important to consider as well and especially if an environmental certification of a building is desired, e.g. Miljöbyggnad. Implementing a methodology developed for early design stages where metrics that interact are evaluated increases the chances of fulfilling the requirements by finding an optimum can facilitate the work for all involved parties.

1.2 Purpose

The main purpose of this Master's thesis is to find a methodology to evaluate the availability of sun- and daylight in early stages of design. In order to evaluate these metrics, the thesis work will also include a regression analysis between exterior available light and the possible amount, which could be supplied into a room inside the building. These correlations will be a necessary basis for the development of the methodology. The intended users of the simulation methodology are actors involved in early stages of building development, before a site plan of a new urban area has been decided.

1.3 Delimitations

This thesis has been delimitated to exclusively include residential buildings in Sweden. The reason is because of the available database used when investigating the correlation for daylight availability (see Section 4.2), mainly contains residential buildings but is solely including buildings in Sweden. However, the developed methodology could still be utilised to provide indications for buildings with other applications, yet there may be larger variations in the result compared to reality. In order to receive a sound correlation this delimitation was considered necessary.

1.4 Method

This Master's thesis started with a broad literature review in order to make sure that the simulation methodology was unique and to understand the current regulations with its metrics. Earlier studies are significant since those are the ones that state what is missing on the market and on which plane there is room for improvement. This thesis has been an iterative process in all steps of the work in order to find suitable solutions, where the three main steps below are presented.

Regression analysis – Based on a database with gathered data of buildings in Sweden a correlation between an exterior and interior metric has been distinguished in order to evaluate the daylight availability in early stages of design. With a Python script, data management was performed by sorting data and further limiting the dataset for the purpose of the analysis. Based on the final dataset, different types of regression analyses have been evaluated in order to find a correlation with a coefficient of determination as close to one as possible.

Methodology – In order to evaluate buildings in early design stages a core simulation structure has been developed. The simulation is developed in the CAD software Rhinoceros supplemented with the calculation plugin Grasshopper. Based on the literature review of existing methods and performed interviews, four key performance metrics for sunlight, daylight and energy have been selected. Thereafter, a simulation methodology has been distinguished including geometry and input handling which is performed manually by the user and creation of surfaces, meshes and calculations of each performance metric performed automatically. The methodology also allows the evaluation of combinations of metrics in order to estimate the availability of the metrics for the simulated building area.

Case studies – To evaluate the flexibility of the developed methodology and as a first step of verification for the established correlations, two case studies have been performed. The case studies provided are two projects in different stages of design located in Sweden. In one of the projects finding an optimized solution by iterations was the aim. The aggregated results including the interacting metrics were improved stepwise. For the other project, an initial verification of the correlation was performed where simulated results of the Daylight Factor were compared to calculated results in another software. Along the working process possible improvements were found in the methodology.

2 Overview of Existing Methods

As Schlueter and Thesseling state in their article about Building Information Models, an indication of the building performance is necessary in an early design process in order to make decisions (Schlueter & Thesseling 2009). Fast and simplified calculations are required with a limited amount of input data (Dogan et al. 2012). As often the case, the required data to run a full-blown simulation is missing. The software that exists is often developed for specialists who perform simulations in a later stage of the design process, where radical changes of the design may not be possible.

For the purpose of calculation of daylight, sunlight, thermal comfort and energy there are many methods and software available. In order to motivate the choice of methodology in this thesis, a literature review of existing methods has been performed. The review emphasizes on giving a short summary of different methods with focus on the workflow and limitations of each method. In the end of this chapter, the findings of the literature review are summarized and important parts of the existing methods are highlighted.

2.1 Description of simulation methods

Shoeboxer is an algorithm-based method with the purpose of evaluating the energy performance of buildings and urban context, in the early stage of design by the means of easy “thermal shoeboxes” (Dogan & Reinhart 2017). The method is based on a 2D drawing of urban context and buildings, where the algorithm generates a 3D architectural model. The level of detail in the model is quite low and only requires volumes in shapes of boxes. The interior space is divided into multi-zones by the use of “Autozoner” (see Section 2.2). Building properties necessary to run the energy simulations are added to the zones by templates. The climate-based insolation analysis is calculated with the use of sensors placed on the façade for the different zones. Regions with similar seasonal solar heat loads are clustered and reference “shoeboxes” are generated based on the calculations above. The boxes are based on both core and perimeter zones. If analyses are performed on a large scale of urban context, building clustering is possible which reduces the simulation time since buildings with similar properties are clustered together.

The shoeboxes with corresponding data is exported to Energy Plus which is a simulation engine that enables running full building energy simulations for both energy use and water usage (Dogan & Reinhart 2017). The energy calculations are based on Energy Use Intensity (EUI). The results of EUI for each shoebox are weighted, extrapolated and colour-mapped back onto the building envelope. The authors emphasize the speed and accuracy of this method, hoping for a wider use in the future.

Figure 2-1, shows the workflow described above in the sense of boxes and arrows. Each box represents a process of the workflow and the direction of the arrows show how data is sent between the processes. Where “API” is mentioned, the authors refer to a process, which takes place automatically, often based on an automated script connected to the intended software or method.

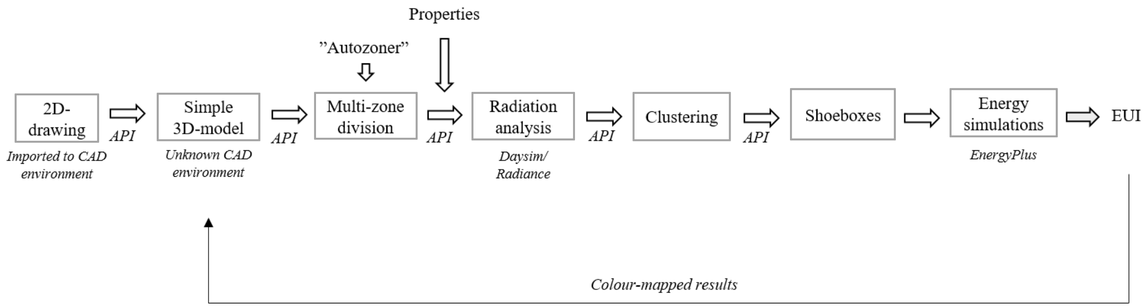


Figure 2-1 Simplified flowchart for the algorithm-based method "Shoeboxer" which enables energy calculations of Energy Use Intensity (EUI) through creating several shoeboxes per building, approximating thermal zones. This method provides sufficient data to perform energy simulations in early planning stages. The notation API stands for 'Application programming Interface" and describes a process which takes place automatically.

Urban Daylight Availability Simulations is a Grasshopper plugin performing simulations in order to investigate the daylight potential of an urban design (Dogan et al. 2012). A simple 3D model of volumes can either be imported or generated in Rhinoceros or Grasshopper. Modifications of the model are performed automatically or manually where the building height is divided into floors. The simulations are split into two parts. First, a script from Grasshopper runs a climate-based hourly radiation analysis in Daysim, a simulation engine for annual daylight calculations with regard to the surrounding climate, in order to calculate illumination levels on the façade. The risk of overheating and potential for solar-based heating is calculated with ray tracing by assuming constant radiation through each patch.

The diffuse solar insolation results are then used together with a linear correlation between exterior radiation and interior daylighting levels in order to calculate the Daylight Autonomy (DA). The correlation requires certain defined values for the façade e.g glacing characteristics, window placement and properties, which leads to simplifications and an induced margin of errors. Further detailed correlation procedure is described in Dogan et al. 2012. Finally, the results can be colour-mapped on the 3D model.

The method has some limitations both concerning the geometry inputs as well as the interpretation of results. However these limitations are under development and suitable solutions are examined, e.g. an algorithm for a database with gathered outcomes of different urban typologies could be used for comparison in order to determine how satisfying the results of the simulations are. The method can be combined with Archsim in order to receive both energy demands and availability of daylight. The process outline described in the text above is presented in Figure 2-2.

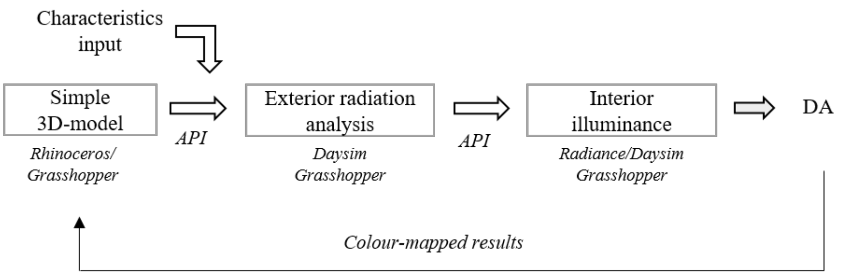


Figure 2-2 *Urban Daylight Simulations described in a simple flowchart of the included processes in order to calculate the Daylight Autonomy (DA). An accompanying script in Grasshopper enables an automated process.*

Urban Modelling Interface (UMI) is a Rhinoceros application tool for urban modelling design with the purpose of evaluating the performance of a neighbourhood (Reinhart et al. 2013). The aspects that are simulated concern daylight, energy use, outdoors comfort and walkability. The buildings and surroundings such as parks, trees, green areas and infrastructure are generated manually in Rhinoceros by the UMI toolbar. In addition, all materials have to be added. In order to run the energy simulations, Energy Plus require that windows are placed correctly in the wall. With the core as basis, the building interior and the partitioning into thermal zones are generated automatically. All the buildings generated in the model are by default set to the same construction type.

The daylight simulations performed in Daysim and Radiance are based on the previous mentioned method "Urban Daylight Availability Simulations", where Radiance is a rendering and simulation engine for ray-tracing. The annual daylight potential is calculated as daylight autonomy (DA) or continuous daylight autonomy (cDA). Furthermore, a thermal comfort analysis outdoors is performed based on the sun- and daylight calculations. The thermal comfort is measured in hours where the ambient temperature is above or below a certain threshold value. For more detailed information, the authors recommend reading Reinhart et al. (2013). The results for each analysis can be separately visualised by an additional coloured layer in Rhinoceros. The workflow of this method is presented in Figure 2-3.

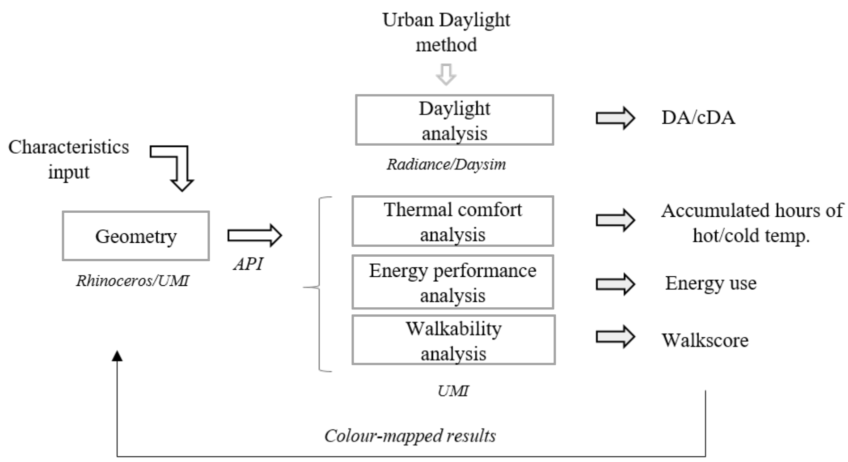


Figure 2-3 *Process outline for the method of Urban Modelling Interface (UMI). The results are presented as Daylight Autonomy (DA) or Continuous Daylight Autonomy (cDA), energy use of the building, accumulated hours for hot or cold temperatures as well as a walkscore.*

Archiwizard is a French developed tool, which is used for evaluating the engineering and architectural design of a building. The software enables a 3D simulation in real time by evaluating the daylighting comfort, thermal comfort and bioclimatic quality of the building. Apart from energy simulations in Energy Plus, the method also enables simulations performed in RT2012, a French verified simulation engine for energy performance calculations. The software allows the user to either import a created 3D-model or to work in parallel with a CAD software to run the simulations. A limitation is the fact that for each new version of the design, the model needs to be reimported in order to update the simulation results (Graitec 2016). The way of how the results for each simulation is presented, is visualised in Figure 2-4.

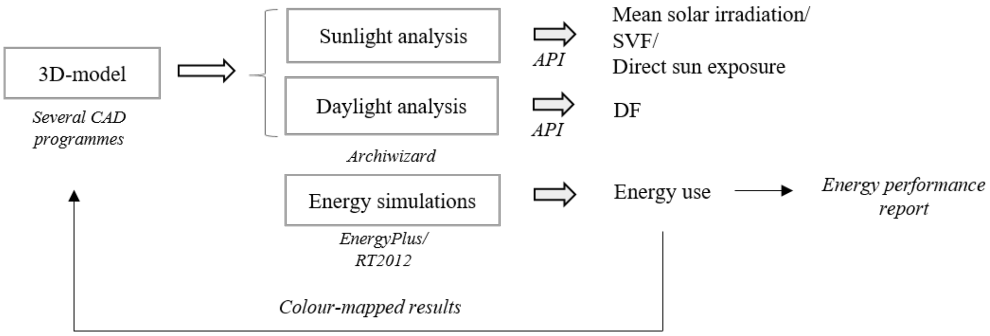


Figure 2-4 Principle process outline for the French software Archiwizard. Analyses for both daylight, sunlight and energy performance are possible to perform. The results for solar radiation and daylight simulations are visualized directly in the model while the energy simulations are performed in Energy Plus or RT2012, where an energy performance report can be exported.

Archsim is a plugin for Rhinoceros and Grasshopper, also included in DIVA 4 to create an energy modelling environment in an early stage of the design process (Archsim n.d.). One can either import or create a 3D model in Rhinoceros or create one using the Archsim toolbox in Grasshopper. Model settings of the building and its characteristics needs to be selected in Grasshopper to ensure a correct analysis. The results from the energy calculations are presented as heating and cooling demands. In order to fully understand all calculation steps, knowledge about Energy Plus is required. The software is under continuous development and at this point it requires to be rerun for each new model update. This plugin is partly based on the method of "Urban Daylight simulations" (Dogan et al. 2012). In Figure 2-5, a process outline shortly describes the workflow of the tool.

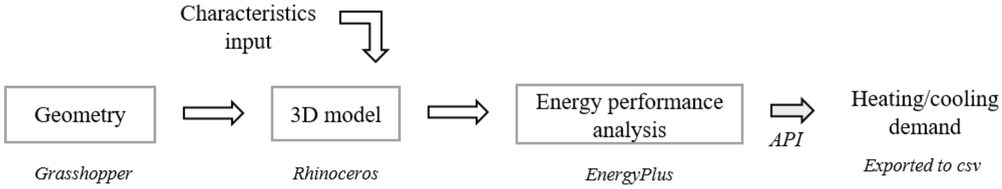


Figure 2-5 Process outline for energy simulations using Archsim. The results for the energy performance simulations are presented in terms of heating and cooling demands.

SEFAIRA Architecture is a web-based software that evaluates a building's energy use and the conditions with regard to daylight (Sefaira 2016). The tool also exists as a plugin to SketchUp. A 3D model is uploaded from either Revit or SketchUp and supplemented with HVAC systems in the software. The daylighting quality of the design is presented in percentage of daylit area, previously described as sDA (see notations). The results for the building's energy use are shown in coloured charts. Daylight visualisation is also available in the software, which shows the percentage of floor area for different values of the daylight factor, as well as areas that are underlit and overlit according to certain threshold values. Figure 2-6 shows a principle sketch of the workflow.

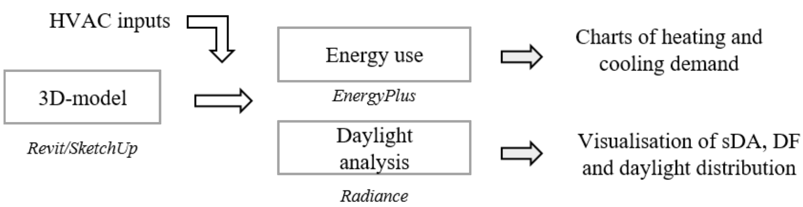


Figure 2-6 Process outline for energy and daylight simulations in Sefaira.The results for the energy calculations are presented in charts of heating and cooling demands while the results from the daylight analysis are shown in a visualisation window for Spacial Daylight Autonomy (sDA), Daylight Factor (DF) and daylight distribution in the building.

2.2 Description of simplified methods

Apart from the simulation tools described in the previous section, it is common to rely on "rule-of-thumbs" or other types of guidelines in an early design stage. This concept together with experience from previous projects give an indication to the architect or building designer whether the design could meet certain requirements or not (Reinhart 2014). In the following section several simplified methods will be described. This section also includes an algorithm which can be combined with the methods described in Section 2.1.

Window-head-height (WHH) is a rule-of-thumb which proposes a relation between the maximum distance into the room where a space is adequately daylit and the distance from the floor to the window head, i.e. window head height. The daylit room depth is a multiple of the WHH distance. Depending on dynamic or static shading the daylit room depth should be between 1 and 2.5 times the WHH (Reinhart 2014).

Daylight feasibility test is another simplified method, which indicates the minimum daylight flux required for a space to be daylit. The flux is calculated as the Window-to-wall-ratio (WWR) times the minimum sky angle and should exceed the value of 2000 (see equation 1) to be able to achieve a space with sufficient amount of daylight (Reinhart 2014). This method is a refined version of the feasibility factor which is described in the document "Tips for Daylighting with Windows" (O'Connor 1997).

$$\Theta \text{ x WWR} > 2000 \qquad (1)$$

Autozoner is an automated algorithm possible to use in early design stages in order to create thermal zones that could be used for energy simulations (Dogan et al. 2015). Typical models to combine the algorithm with are based on building volumes. The Autozoner supports creation of thermal zones for both 2D drawings with extrusion of building height and 3D models. The algorithm handles the subdivision of zones in different steps providing as accurate thermal zones as possible on a simple geometry. Windows are provided based on window-to-wall ratios (WWR). Figure 2-7, shows an example of how the algorithm can be used in energy modelling.

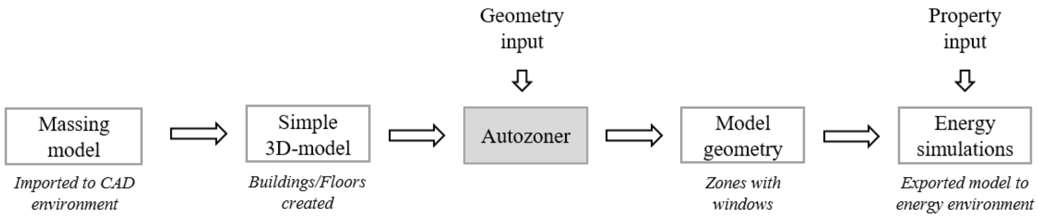


Figure 2-7 Principle flowchart for the integration of "Autozoner" into an energy modelling process. The figure has been interpreted from the original source (Dogan et al. 2015).

The Building Research Establishment (BRE) has developed a set of guidelines for sun- and daylight simulations mainly valid in the United Kingdom and the Republic of Ireland (Littlefair 2011). This guide's purpose is to help and support designers, architects and engineers to design new buildings with regard to parameters affected by sun- and daylight. Based on statistics, charts and diagrams have been compiled to support the calculations but also to give indications of a building's ability to fulfil the local building regulations. Compared to the methods described in the previous section, this method is analogue and is not based on simulations. Although, it provides indications from calculations of geometrical parameters as obstruction angle and Vertical Sky Component but also of a mean Daylight Factor. Out of the results and classifications of certain analysis points, several suggestions of solutions are presented depending on which indicator that has been investigated.

2.3 Summary

The conclusions from this review are that the existing methods of today have a similar approach in the evaluation of metrics for sunlight, daylight and energy but it seems like they in practise are suitable in later stages of design. The presented methods either require a higher level of details in the models or have limitations with regard to the automatization of the software. In the following section, the most important advantages of the studied methods will be highlighted.

From the simulation methods described in Section 2.1 several approaches of designing in early stages have been embraced. The metrics used are of interest since they interact with each other. The way of working in a CAD environment with additional plugins has also been considered a strength. This is due to the way of communicating results and visualisation of results of an analysed area. The parameters which have been included in the developed simulation methodology (see Chapter 4) concern the result presentation through coloured layers in Rhinoceros, the handling of both 2D and 3D geometry with simple input data and the high automatization in order to receive a quick response.

Regarding the energy aspect the priority has been considered less important in these early stages. However, simplified ways of indicating an object's energy performance has been kept in order to not exclude it completely.

The simplified methods presented in Section 2.2 illustrates the strength in achieving indications of new urban areas by simplifications with results accurate enough to base decisions upon. These methods does not include any CAD or simulation software, it is more of an estimation approach based on guidelines. An adapted WWR approach has been included as an input data in the developed methodology.

3 Key Performance Metrics

In order to fully understand the methodology derived from this thesis work, this chapter aims to give a short overview of the key performance metrics. The key performance metrics have been chosen based on the literature review of existing methods in combination with performed interviews with the municipality and discussions with supervisors.

The following chapter will include metrics, which either have been used in the daylight-based regression analysis (see Section 4.2) or are a part of the developed simulation structure. For each metric, there will be a description of the main focus in order to avoid confusion. If threshold values or regulations exist, these will also be mentioned in the following chapter. The key performance metrics are related to daylight, positive and negative effects of sunlight and thermal transmittance. The positive effects of sunlight concerns the required amount of sunlight in each room (see Section 3.1.1) and the negative impact includes the risk of overheating due to large amount of solar heat load (see Section 3.1.2).

3.1 Key performance metrics for sunlight

The main part of the solar energy is absorbed or reflected in the atmosphere and only a small part of the sunlight hits the surface of the earth, this phenomena is called solar irradiance (Andrén 2007). The solar irradiance consists of a direct and an indirect component, where the indirect component includes sunlight, which have been scattered in the atmosphere or reflected by surrounding objects or surfaces. Knowledge about the direct and indirect components are important when modelling due to their effects on the different sky conditions, but also to know what to include and what to disregard in the simulations. For a clear sky (see notations) the direct sunlight component is the main contributor whereas for an overcast sky it is the diffuse sunlight component which has the biggest impact on the modelling results (Reinhart 2014).

The solar irradiance on a surface is often in direct relation to the risk of a large amount of sunlight, which can cause excessive heat in a room. Cooling equipment, resulting in a higher energy use of the building, could often solve the issue of excessive heat. Since the maximum level for energy use according to Swedish building regulations is constantly decreasing, this fact is important to be aware of when designing. In the developed methodology this issue will be evaluated as solar heat load, which makes it possible to compare to environmental certification systems as well.

Apart from the solar heat load, there are regulations regarding the direct sunlight in a room that needs to be taken into consideration when designing. This consideration can easily be forgotten since it is not measured in most of the environmental certification systems, nevertheless is a very important parameter affecting the well being of humans. The parameter is evaluated through the amount of hours of direct sunlight.

3.1.1 Hours of direct sunlight

The amount of sunlight hours in a room is dependent on the location, i.e. geography and the obstructions surrounding the building. According to Swedish building regulations, there are requirements regarding the direct sunlight in an occupied room. It is stated that a room occupied more than temporary needs to have direct sunlight, i.e. sunlight which has not been reflected (BBR24 2016).

Regarding evaluation of a reasonable amount of sunlight hours in a room, the publication "Solklart" by Boverket states a desired value of five hours at vernal equinox for buildings and outdoor recreations, such as playgrounds and courtyards (Boverket 1991). Other existing threshold values are four hours. In the simulations this means that all façades need to achieve four to five hours, and if not, the design needs to be changed. Due to the path of sun, façades facing north will not receive as many hours as required. A common solution for this issue is to choose an implementation of rooms with windows in two directions or to be aware of this when choosing the layout of the building. In this thesis, the threshold value used is four hours.

3.1.2 Solar irradiance and solar heat load

For a building situated on the northern side of the equator, surfaces facing south are exposed to the maximum intensity of the sun. Since the sun rises in east and descends in west, the solar irradiance on the façade in these directions will depend on the time of year, which affect the angle of incident. One can say that the solar heat gain depends on three main parameters; the position of the sun around the z-axis corresponding to time of year and the angle of incident, the period of time for irradiance on each façade and the thermal inertia of the building. For a summer period when the sun rises early and sets late in the evening, the building accumulates heat during the day. When the sun hits the façade facing west with a flatter angle in the evening, it is usually problematic to maintain a good indoor climate. For this purpose, the effect of building orientation needs to be accounted for during the design process.

As mentioned in the beginning of this chapter, the solar radiation can have both a positive and negative effect on a building. To reduce the negative effect, the heat gain and risk of overheating, the building can be oriented in such a way that the solar radiation into the room is minimized. Other ways to limit the solar heat load in a room are to use solar shadings and glass coatings. The main purpose of the solar shading is to prevent the solar radiation of entering the room. Glass coatings are often used when the light transmittance want to be kept high, while limiting the solar energy, as infrared radiation, into the room (Frost et al. 2012). For a building with high solar heat load, both glass coatings and shadings can be essential in order to achieve a good indoor climate.

In this thesis, the solar irradiance is simulated over a year, taking into account the parameters mentioned above and then transformed to a potential solar heat load (SHL) in a room. The calculation of solar heat load is similar to the equation used in Miljöbyggnad 2.2, apart from that the maximum solar irradiance in this thesis work is achieved by an annual simulation based on weather data and location of the building. This is more realistic than using the assumed value of 800 W/m^2, used in east-to-west direction in Miljöbyggnad, which is independent of location.

Equation (2), shows how the solar heat load is approximated in this thesis work. In the methodology, it will also be possible to compare the results to Miljöbyggnad 2.2 in order to check if the limits are possible to achieve. The limiting values for grading in Miljöbyggnad have been used as threshold values in order to aggregate this metric, which will be further explained in Chapter 4.

$$SHL = \frac{I_{sun.max} \ x \ \frac{A_{glass}}{A_{wall}} \ x \ 1m^2 \ x \ g_{glass} \ x \ g_{shading}}{d_{room} \ x \ 1 \ m} \ [W/m^2] \qquad (2)$$

3.2 Key performance metrics for daylight

Daylight includes the natural part of sunlight which can be seen by the naked eye (Eriksson & Waldenström 2016). There are several ways of measuring daylight, either by measuring the amount of luminance in a room or the daylight availability at the level of the façade. In the following section, selected performance metrics will be shortly explained.

Since this thesis is partly based on the results of a Master thesis from 2016 (Eriksson & Waldenström 2016), which describes the daylight parameter more in depth, the authors recommend this report for further reading about daylight.

3.2.1 The Median Daylight Factor (DF_{median})

The most common way of evaluating the daylighting levels in a room is based on Daylight Factor calculations. Since this type of calculation requires specified room parameters, window properties and placement, the procedure is not feasible in the early stages of design. In this Master thesis, this indicator is therefore evaluated through the median DF, based on a developed correlation (see Section 4.2). The median value of the DF represents the middle value of the result for a set of investigated points in a room.

The previous work of Eriksson and Waldenström (2016) showed a clear linear regression between the median and the point specific value of the Daylight Factor in a room. For the investigated buildings, the results showed a very similar pattern of the distribution of the DF, which resulted in the conclusion that the calculation of the DF in a specific point could be replaced with the median value, in early design stages.

According to the Swedish building regulations, the Daylight Factor in a specific point (DF_{point}) has to exceed 1.0 percent (BBR24 2016). By assuming that DF_{point} and DF_{median} are equal, the same limiting value would be valid for DF_{median}. In the developed methodology, the limiting value is dependent on whether the investigated project is aiming to be environmentally certified or not, though the minimum threshold value is still according to BBR.

3.2.2 Sky View Factor (SVF)

There are different definitions of the metric Sky View Factor. In order to be transparent and avoid confusion, this thesis will use the following definition, which is the same definition used in the script-based components in Grasshopper, used when modelling.

The Sky View Factor describes the amount of sky viewed from a perspective of a surface or a set of surfaces. This means that the metric takes obstructions into account, e.g balconies, trees and surrounding buildings. The sky hemisphere is divided into patches where the incoming light through each patch is weighted against the patch area. The closer a patch of the sky is to zenith, the more it is weighted, called cosine weighting (see notations). The metric is based on a uniform sky (Zhang et al. 2012). For a vertical surface the theoretical maximum value for the Sky View Factor is approximately 50 % visible sky for an unobstructed surrounding (Oke 1987).

3.2.3 Sky Exposure Factor (SEF)

The sky exposure factor is based on geometry and expresses the amount of sky visible from a certain point. The calculation procedure is performed in the same manner as for SVF, but with the difference that all patches of the sky are equally important. This metric is based on a uniform sky as well. A point placed on a vertical surface has a theoretical possibility to reach a SEF of approximately 50% (Zhang et al. 2012).

A summary of the key performance metrics for daylight is presented in Table 3-1. All metrics are horizontally based, meaning that the modelled hemisphere is independent of the simulated surface and none of the metrics are sun dependent.

Table 3-1. Summary of metrics and their bases when modelling.

Metrics	Sky type	Reflections	Cosinus weigthed
Sky View Factor (SVF)	Uniform sky	No	Yes
Sky Exposure Factor (SEF)	Uniform sky	No	No
Daylight Factor (DF)	CIE Overcast sky	Yes	Yes

3.3 Key performance metrics for energy

Since this thesis focuses on the early stages of the design process, several factors affecting the energy performance of the building are not determined. However, an initial indication of the performance is possible by evaluating the mean thermal transmittance (U_m-value) of a building. It can be of great importance in order to indicate whether the design is acceptable or needs adjustments to improve the performance of the building.

The U_m-value of each building is calculated based on equation (3), which is a simplified equation from BBR. The reason why the thermal bridges have been excluded is because at an early stage of design, the expected amount of linear and point-based thermal bridges is hard to predict.

$$U_{mean} = \frac{\sum_{i=1}^{n} U_i A_i}{A_{om}} \qquad (3)$$

According to equation (3), the U-value for each component is required. If this prerequisite exists in the early stage it should be used at first-hand. Otherwise, the recommended values from Swedish building regulations should be strived for, see Table 3-2 (BBR21 2014). If available, the thermal bridges should be included for each construction element. In order to achieve as accurate indications as possible, the thermal bridges should be specified from the producer. If not, an additional factor in percent could be used as a simplification, though it is not recommended.

Table 3-2 Standard U-values for construction elements excluding thermal bridges (BBR21 2014).

U_i	$[W/m^2K]$
U_{roof}	0.13
U_{wall}	0.18
$U_{foundation\ (no\ soil\ included)}$	0.15
U_{window}	1.2
U_{door}	1.2

Depending on the climate zone and type of heating system, the U_m-value for smaller one-family houses and multi-family houses are limited to approximately 0.40 (BBR21 2014). This value together with experience from the supervisors of Bengt Dahlgren has been used in the development of methodology.

4 The Developed Tool for Early Evaluation

As mentioned in Chapter 2, several existing methods available on the market today requires more advanced and detailed 3D models. Most of the methods are implied to be used for early stages of design, however, detailed input data is required. This is a limitation both to the users and to the application of the methods in a preliminary design stage. It is therefore the idea that the developed methodology should be based on simple geometry but still be able to provide indications of the design's ability to fulfil a sufficient amount of sunlight, daylight and thermal transmittance. The methodology should include a high level of automatization and produce clear results, which are easy to interpret.

Based on the choice of performance metrics, described in Chapter 2, a methodology of how to perform simulations of sun- and daylight and thermal transmittance in early stages of design has been developed. In the following chapter, the developed methodology will be described as well as the necessary correlations that have been derived throughout the thesis work. Starting with a methodology overview, the chapter then presents the prerequisites in order to evaluate daylight availability, based on a correlation between the DF_{median} and the exterior metric, the SVF. The findings of the regression analysis are presented in Section 4.2. The main focus of the chapter lies in explaining the developed simulation structure which is described in Section 4.4.

4.1 Methodology overview

The methodology is developed according to a certain simulation structure presented in Figure 4-1. The CAD software Rhinoceros is the basis of this methodology, supplemented with the calculation and simulation plugin Grasshopper 3.0 that the simulation structure is built in. The simulations have been performed with components based on Pyhton scripts included in Grasshopper and the environmental plugins Ladybug 0.0.64 and Honeybee 0.0.61, which uses the simulation engines Radiance 5.0 and Daysim 4.0 to run the simulations.

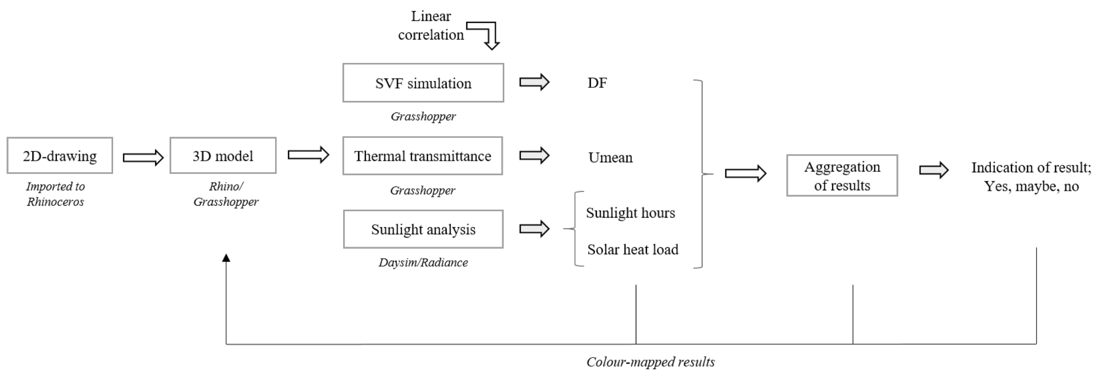


Figure 4-1 Principle flowchart of the derived methodology called Building Design Sketcher. The figure shows the basic structure of the methodology. The results are displayed in actual values, aggregated values and total summed values.

As Figure 4-1 shows, the simulation structure has been divided into several steps. The first part includes importing a blueprint, management of geometries and assigning building properties to the model, which is performed manually. Thereafter, all steps of the methodology are performed automatically where grids are assigned; the calculation of each metric is performed in parallel, either by a distinguished correlation or by existing components in Grasshopper. It is possible to achieve indications of the DF_{median}, number of Sunlight Hours, Solar Heat Load and an U_m-value of each building. The results are afterwards processed in order to be presented on different aggregation levels. Each metric can be achieved separately and the results can be broken down to be able investigate the conditions individually.

In Appendix D, a user manual of the methodology is introduced where snapshots and descriptions of the simulation structure are presented. In Section 4.4, a detailed description of the developed simulation procedure will be described.

4.2 Regression analysis of DF_{median} and an exterior metric

In order to evaluate the daylight availability in early stages of design, where the floor layout of the building is not yet determined, the calculation procedure needs to be based on another metric than the point specific value of the DF in an actual room. Therefore, the first stage of the methodology development focused on finding a reliable correlation between an exterior metric, which should be easy to evaluate, and the DF_{median} in a fictive room inside the evaluated building. By finding such a relation, the daylight availability can be evaluated based on a simple building volume with surrounding shading objects and give indications of the levels of daylight distribution of the investigated building.

In the Master's thesis performed in the spring of 2016 at Bengt Dahlgren AB, a promising correlation of the DF_{median} and a vertical DF on the outside of the façade, DF_{window} was found (Eriksson & Waldenström 2016). Based on their result, the intended correlation has been further developed to include another exterior metric, one, which is dependent on the surrounding conditions outside and more appropriate for the approach of the developed methodology. The main purpose of the correlation makes it possible to evaluate and improve critical buildings where the DF_{median} is below 1 %. Therefore, the most important part of the correlation focuses on rooms with a DF below one percent.

Based on a database with approximately 25.000 simulated rooms in buildings situated in Gothenburg, Stockholm and Lund, a Python-script was used to import, filter and process data. In the iterative process of investigation, several metrics were evaluated and for each evaluation a regression analysis was performed where linear, polynomial, second order and exponential regressions were assessed. The investigation included the exterior metrics SVF and SEF, which have been compared to the interior DF_{median} in each simulated room. A more detailed description of the workflow, filtering criteria and how the correlation was distinguished can be found in Appendix A.

The resulting dataset, after the data management process, conclude seven residential buildings in Gothenburg with approximately 500 simulated rooms. Figure 4-2, shows the findings of the investigation.

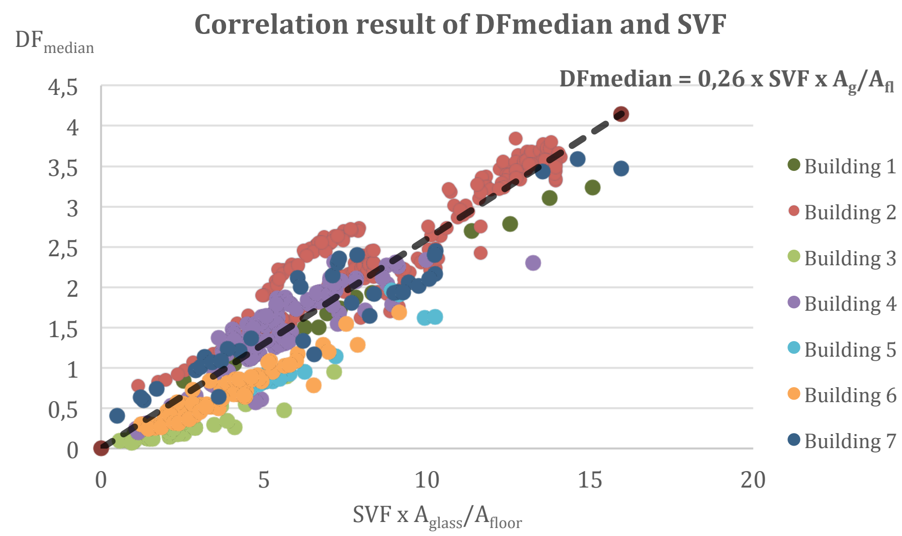


Figure 4-2 The result of the investigation where the linear regression of the DFmedain and the SVF is presented. Each building has been colour-plotted in the chart where one point represents the value of a simulated room in each building.

The result of the study showed a linear correlation between the DF_{median} and the SVF accompanied with the ratio of window area to floor area in a fictive room (see equation 4) with a coefficient of determination of $R^2 = 0.86$. The fact that the SVF takes obstructions into account as well as it corrects the angle of incident (cosinus-correlated, see notations) strengthens the choice of metric. The quotient of window area divided by room floor area, is a common ratio used in the design processes and is limited to at least 0.1, i.e. 10 % (BBR21 2014).

$$DF_{median} = 0{,}26 * SVF * \frac{A_{glass}}{A_{room.floor}} \quad [\%] \qquad (4)$$

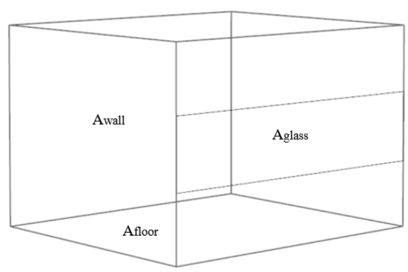
A_{glass} = Glass area [m^2]

$A_{room.floor}$ = Floor area of a fictive room [m^2]

4.3 Geometry relation

In order to transform the solar irradiance on the vertical surfaces into a solar heat load in a fictive room as well as calculating the thermal transmittance for each building, equation (5) was established. The equation presents the area correlation between the interior glass-to-floor and the exterior window-to-wall ratio. The correlation was found by setting up a simple model with mathematical expressions and by the use of algebra resulted in the equation below. The steps of the calculations are presented in Appendix B.

$$\frac{A_{glass}}{A_{wall}} = \frac{A_{glass}}{A_{room.floor}} * \frac{d}{H_{floor}} \quad [-] \qquad (5)$$



A_{glass} = Glass area [m^2]

A_{wall} = Area of external wall [m^2]

d = Assigned room depth [m]

H_{floor} = Height per floor (including floor slab) [m]

4.4 Description of Simulation Structure

This section aims to describe the structure of the simulation methodology. The description has been divided into different steps, which reflects upon the main parts of the methodology. It includes the handling of input data and assumptions, the main simulation steps for each metric, how the results are aggregated and finally presented to the user.

4.4.1 Input data and assumptions

In order to evaluate an urban context, the first input to the methodology are geometries representing buildings and surroundings. These geometries are generated by drawing a building circumference of its footprint and assigning a height to each building that should be evaluated in Rhinoceros. This is easily done by importing a 2D drawing as a blueprint and drawing each line on the canvas. The surroundings, obstructions around the building in form of other buildings, balconies, trees, sheds etc. can be added in the same manner. To speed up the process, it is also possible to import a 3D model and use the 3D shapes to assign the heights of the buildings and surroundings.

By the use of assigning the building circumference as lines, no limitations exist concerning different shapes of footprints in the methodology. There is though, a limitation of geometry handling by means of all building circumferences have to be drawn with lines in Rhinoceros and that 3D models cannot be assigned directly as a building geometry. See Chapter 7 for suggestions on future improvements. In order to perform the simulations with the developed methodology, the following inputs are required:

- Building height
- Number of floors
- Assumed room depth of a fictive room
- Thermal transmittance
- Area glass to area floor ratio (excluding frames)

In order to evaluate what the solar heat load could be in a room, input of different types of shadings and glass coatings are optional. Approximate values for shadings and coatings are presented in Appendix C.

4.4.2 Calculation steps

The different simulations performed in the developed methodology are grid-based, where a calculation mesh is automatically applied to the objects of interest. A grid-based calculation enables flexibility to the user concerning how to visualise and extract result from the model compared to pixel-based calculations where the user chooses a view to render the result, only by coloured pictures.

Since the main purpose is to evaluate the walls of the buildings in an urban context, this means that it is on the vertical surfaces the calculations are performed. The meshes of the surfaces of interest are grouped and the rest of the surroundings are seen as obstructions shading the simulated buildings. An example of this is shown in Figure 4-3.

Depending on the shape of the building, e.g. overhangs or direction of the walls in contrast to the position of the sun, the building could shade itself. This fact needs to be accounted for by adding the buildings' surfaces to the group of obstructions as well. If desired, there is also a possibility to evaluate horizontal surfaces as streets and surroundings since this often is a part of planning new areas. In order to achieve this evaluation it is only a matter of which surfaces to add to the simulation.

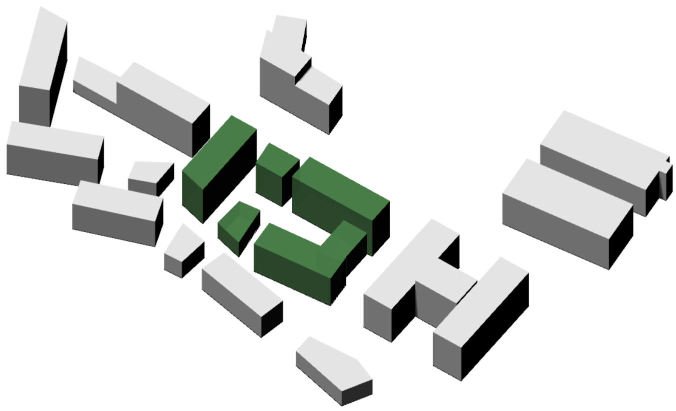


Figure 4-3 Principle sketch of an investigated area. The green group of buildings are surfaces of interest and the rest of the buildings (in grey) are the surroundings, which are considered as obstructions.

From these set of simple geometries with belonging meshes, three different types of simulations are pursued which concern the evaluation of daylight, sunlight and thermal transmittance. The daylight availability is calculated based on the DF_{median}, the effect of solar irradiance based on sunlight hours and solar heat load and finally the U_m-value is evaluated for each building of interest.

The median Daylight Factor

The availability of daylight is assessed by simulating the SVF for each point in the grid and based on the established correlation in equation 4 (see Section 4.2), the DF_{median} is calculated. Since the correlation transform the exterior value of the SVF to an interior indication of the DF, the result of this analysis is presented for a fictive interior room for each point in the grid. The SVF (see section 3.2.2) is calculated based on a view analysis in Grasshopper, a geometric analysis, where the visibility of a sky hemisphere is assessed as percentage of visible sky in each point of the grid.

Calculation of sunlight hours

The next step of the simulation is to evaluate the amount of sunlight hours. This is performed by creating a solar hemisphere around the objects of investigation, which is produced, based on the location of the sun during an elapsed year from a selected Energy Plus Weather-file (epw-file). Based on the path of the sun, the sun vectors are calculated for each point in the grid by the use by ray-tracing. The sun vectors describe the direction of the sun on the path in connection to the measured point (see Figure 4-4). The amount of sunlight hours per grid point, according to section 3.1.1, is then calculated for the time of vernal equinox, based on these vectors and the geometry of the study, i.e the façade surfaces and the surrounding context.

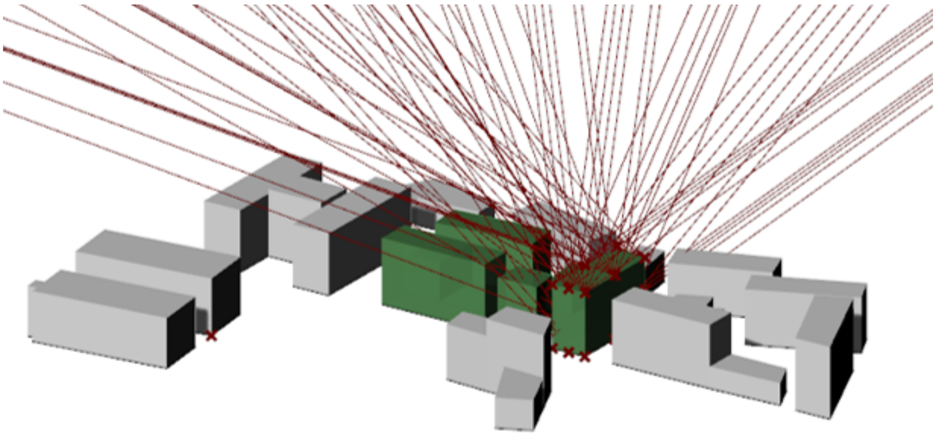


Figure 4-4 Example of ray-tracing of sun vectors from each point in the grid to the position of the sun at the time of investigation. Depending on which time of year, the position of the sun differs but the procedure stays the same.

Solar heat load simulation

The effect of the solar irradiance on the façades is evaluated in terms of solar heat load for a fictive room in the building. In order to calculate the solar heat load, the solar irradiance need to be simulated first. The purpose of the simulation is to find the maximum value of the solar irradiance in each point of the grid during a year. It is based on annual calculations, where the building geometries along with its mesh, surroundings and material properties are supplemented. This simulation is performed by Radiance 5.0 and Daysim 4.0, based on ray-tracing where the size of the radiation for each ray is calculated. By using Daysim, the methodology enables climate-based calculations where an epw-file is used to generate the sky and sun conditions.

The methodology calculates both direct and indirect solar radiation for each hour of a year, corresponding to a large amount of data for each point in the grid. Since one part of the aim of this methodology is to achieve a potential for good thermal comfort indoors, which the solar heat load affects, it is mostly the direct solar irradiation that contributes to a higher value of the solar heat load. This means that the diffuse light can be limited in the simulations. By limiting the ambient bounces, the number of reflections is limited; in this case they are limited to one bounce per ray. The output from these annual simulations is a file of irradiation values for each point in the grid and for each hour of the year. The maximum value for each point is then established and the solar heat load is calculated.

The thermal transmittance calculation

Based on equation (3), see Section 3.3, the U_m-value for each building investigated is calculated. According to the equation, the specific thermal transmittance for each construction element, including thermal bridges if available, and the areas of the different construction elements are required. In order to enable create one building with different building heights (see Figure 4-5), the estimation of the U_m-value will have an integrated margin of error. This is due to the construction of a modelled building consisting of several buildings with different input data merged together. This will lead to that there will be surfaces that does not face the outside, yet they are considered as such leading to an increased U_m-value of each building which is not correct but still on the safe side.

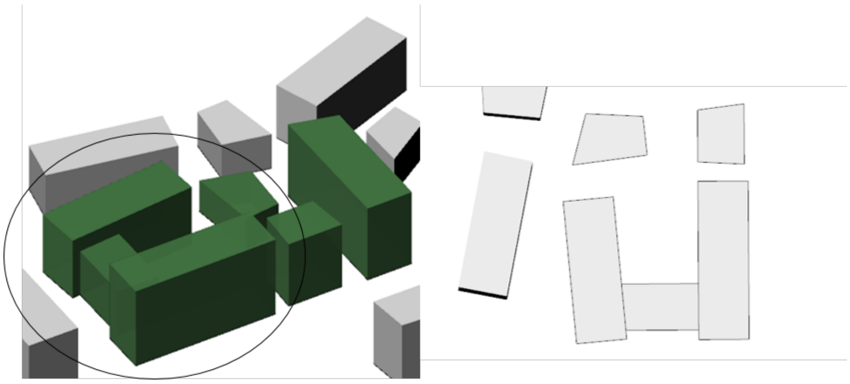


Figure 4-5 When buildings have different heights in the same building body, the procedure of drawing the building circumference becomes that each building section has to be drawn separately. For this case three buildings have been created separately which affects the U_m-value of the building.

4.4.3 Visualisation and aggregation of results

The visualisation of results has been divided into three parts. After performing the simulations, the user can choose the results of interest and display them by colour-mapping the 3D model in Rhinoceros. For each evaluated metric, the results are presented in actual values and the presentation allows the user to evaluate metrics separately.

The next step of the evaluation is to assess the combination of the metrics. In order to assess these combinations, the result from each simulated metric need to be aggregated. The end result of the aggregation should be in form of an indicating value; Yes, Maybe or No. Therefore, by using threshold values, each metric are aggregated into these the indicating categories, where the colour green represent yes, yellow – maybe and red represent no. The thresholds are based on suggested values or regulations according to Chapter 3, where an interval is created for each endpoint indicator.

The results are displayed per aggregated metric, also by colour-mapping the model, where one could see which areas that are underperforming and need adjustments. Depending on which grade of Miljöbyggnad that is strived for, different threshold values applies. Table 4-1, shows the threshold values for the grade bronze. The limiting values for Silver and Gold according to Miljöbyggnad can be found in Appendix C.

Table 4-1 Aggregation of results for each metric, where the Daylight Factor and the Solar Heat Load are based on Miljöbyggnad Bronze.

	Yes	**Maybe**	**No**
Daylight Factor [%]	>1.1	0.8 – 1.1	< 0.8
Sunlight Hours [h]	> 4	2.5 - 4	< 2.5
Solar Heat Load [W/m^2]	<36	36 - 40	> 40
U_m-value [W/m^{2}K]	< 0.3	0.3 – 0.45	> 0.45

The final step of aggregation is the combination of three out of four metrics, where a summation is performed. For this total aggregation, the U_m-value has been determined as a separate metric. This is due to the fact that this metric is weighted for the whole building while the other metrics are calculated for each test point in the grid.

Based on the result of the first aggregation of each metric, a summation is performed and from the number of Yes, Maybe and No, a total categorization is established. Figure 4-6, shows a principal flowchart of the aggregation process explained above.

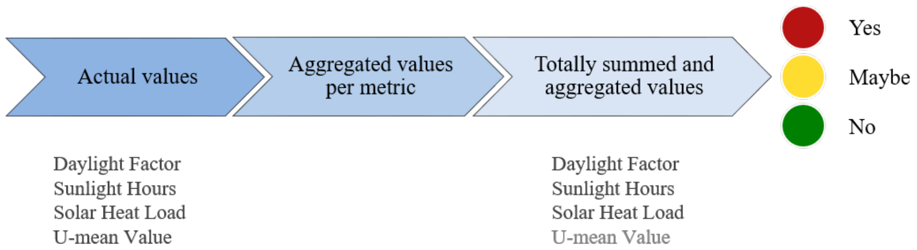


Figure 4-6 Principal flowchart of the aggregation process of results. The actual values and aggregated values can be visualised per metric (DF, Sunlight hours, Solar heat load and U_m-value). The aggregation process finally leads to a total sum where for each point in the grid, a combined result is calculated. The U_m-value is added separately.

In Table 4-2 the limits for each group is presented. If one or more than one No exists from any of the metrics in the evaluated point, the final result for that point will be No. In order to be categorized as Yes, a point needs three out of three of Yes. Concerning the intermediate categorization, a point needs at least one Maybe and the rest Yes in order to be placed in that category. The final result is also colour-mapped onto the geometry with the same colours for the yes, maybe and no categories as for the first aggregation.

Table 4-2 Number of aggregated results for a certain grade of the total summation.

	Yes	**Maybe**	**No**
Aggregated summation	3 Yes	≥ 1 Maybe + the rest Yes	≥ 1 No

The asset of the interpretation of results is that the results are coloured in the model directly (see Section 5.1.3 for example of result presentation). Additionally, there are possibilities to assess each metric individually if for example only one metric is of interest. The authors wants to point out that the displayed results only indicates whether the arrangement of buildings have proper qualifications to fulfil the regulations or not. The outcome of this methodology should be more of a guideline how to find the hotspots that needs modifications rather than a truthful correct answer.

5 Initial Verification through Case Studies

The evaluation through case studies serves two purposes; one is to evaluate the developed methodology in order to discover weaknesses in the simulation process and management of data, while the other purpose is to verify the estimation of the Daylight Factor that is based on the distinguished correlation. The assessment has been based on two representative case studies. The first case study focused on the evaluation of the simulation structure in the developed methodology (see Section 5.1) while in the second case study, the simulation result of the median Daylight Factor was compared to calculated results from another software (see Section 5.2).

5.1 Evaluation of the developed methodology

The different calculation steps and visualisation of results, previously described in Chapter 4, will be evaluated in this section. The purpose of the study is to assess the user flexibility, but also to find deficiencies and improvements of the developed methodology. The initial design of a residential building development has been evaluated and stepwise improved in order to achieve a better design of the building. The case study is a project in Gothenburg where the site plan of the area is determined, which allows minor adjustments in the design. Through the iterative process of evaluation, different parameters of the design will be edited and the results will be presented for each step of improvement of the design.

5.1.1 Case study 1 - Lindholmshamnen

The first case study is a project called Lindholmshamnen, located on Hisingen, on the Northern side of Göta älv in Gothenburg. The area is planned by Älvstranden Utveckling AB together with the Department of City Planning in Gothenburg (Älvstranden Utveckling AB 2016). Today, the area is a parking lot with some existing buildings with different kinds of activity, however, no residential buildings exists. Due to the present exploitation of the area, several buildings will be constructed, especially residential buildings. The project is therefore suitable since it is in the phase when it is focusing on adjusting parameters such as share of windows, room depth and number of floors. Figure 5-1 shows the developing area of Lindholmshamnen.

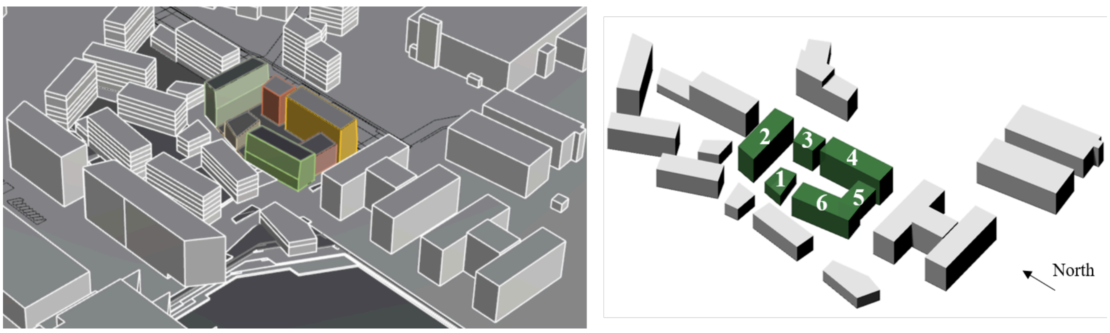


Figure 5-1 Developing area of Lindholmshamnen (to the left) and how the model is created (to the right) based on provided 3D models. The six green buildings are included in the study and the surrounding buildings are added as shading objects.

5.1.2 Geometrical condition and assumptions

The geometrical conditions for the six green buildings shown in Figure 5-1 are presented in Table 5-1. The geometry of the buildings, including the size and heights, was provided in the model from the architect. Due to the limitation of the concerning tilted walls, the walls of building 1, 4 and 6 have been modelled as completely vertical surfaces. Building 4, 5 and 6 are initially one building, but in this case study modelled as three separate buildings, due to the different building heights which is regarded as a simplification. The number of floors has been assumed, based on reasonable floor heights of approximately 3 meters, including floor and ceiling slabs.

Table 5-1 The specific parameters for each building in the model. These parameters are fixed and cannot be modified throughout the simulations.

	1	**2**	**3**	**4**	**5**	**6**
Height [m]	10	23	20	24	14	18.5
Number of floors	3	7	6	7	4	6
Number of façades	4	4	4	4	4	4

The building characteristics presented in Table 5-2 are parameters, which are possible to adjust depending on the results from the first simulation. The values in the table were unknown and therefore initially selected based on building regulations, see Chapter 3, or based on reasonable assumptions where the same inputs were selected for all buildings. For each iteration in the case study, some of these values have been adjusted in order to improve the design results. The shading and glass properties were selected according to approximate values from manufacturers and are equal to simple interior shading and a clear glass, i.e. without any coating.

For the aggregation of results in this case study, the Miljöbyggnad grade to strive for was set to Silver. The input data for the different iterations can be found in Appendix E.

Table 5-2 Initial selected values for the adjustable parameters in the model, valid for all buildings investigated. These parameters can be adjusted in order to improve the design without violating the regulations determined in the local site plan.

Parameter	**All buildings**
$A_{glass}/A_{room.floor}$ [-]	0.10
Room depth [m]	4.5
Shading factor [-]	0.7
g-value [-]	0.7
U_{window} [W/m^{2}K]	1.2
U_{wall} [W/m^{2}K]	0.18
$U_{foundation}$ [W/m^{2}K]	0.15
U_{roof} [W/m^{2}K]	0.13

The number of grid points for this study was set to 1200 points in total which was considered to be accurate enough for making decisions based on the results and at the same time limiting the simulation time in order to facilitate the iterative process.

5.1.3 Simulation results

The results given after running the simulation with the initial design of the building clearly shows challenges for this area. Figure 5-2, shows the total aggregated result for the first simulation in form of three colours. This result is the total sum of the number of Yes, Maybe and No for each metric evaluated per point in the grid. While the values for the vertical façades have been weighted for each point, the thermal transmittance have only been aggregated and plotted per building (on the roof), indicating its energy performance in the same colours.

The green areas are considered to be adequate with regard to the four evaluated metrics; DF_{median}, amount of sunlight hours, solar heat load and the U_m-value. Concerning the yellow areas of the buildings, these are considered as uncertain and can be improved by adjusting the input parameters. This interval could for example contain both areas, which achieve enough daylight but at the same time do not meet the requirement for sunlight hours or solar heat load, which will result in a lower grading level. For the red coloured areas, the requirements for at least one metric have not been reached.

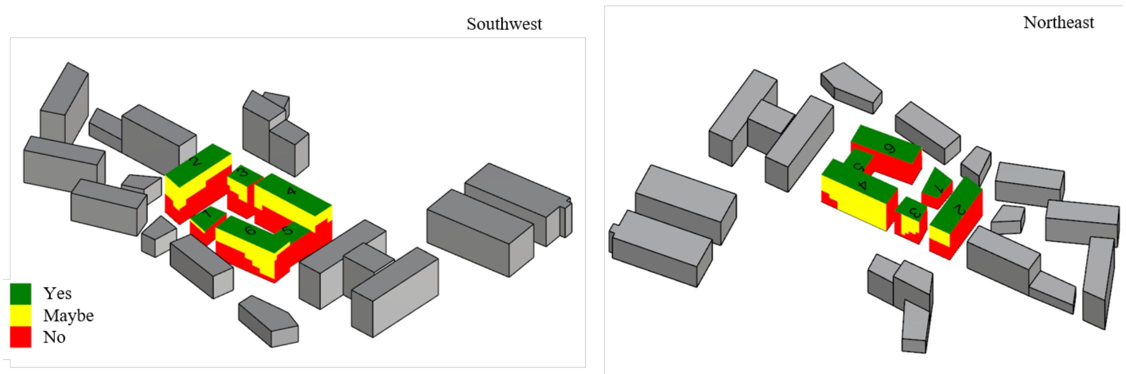


Figure 5-2 *Total aggregated results for the initial simulation of case study 1. The weighted and aggregated result for the vertical surfaces is presented for each point in the grid. The mean thermal transmittance, the mean U_m-value, is colour-mapped on the roof of each building.*

The main reason for the outcome of this simulation was due to the short distances between the buildings, which lead to an increased level of obstructions and questionable results for the four indicators. This parameter could not be adjusted in this stage of design. Other parameters that were possible to attune in order to achieve better results were; the glass-to-floor ratio (GFR), the room depth of a fictive room inside each building and shading parameters including different glass coatings.

First iteration

By increasing the GFR to 30 % and decreasing the room depth to 4.0 meters, the following results were achieved (see Figure 5-3).

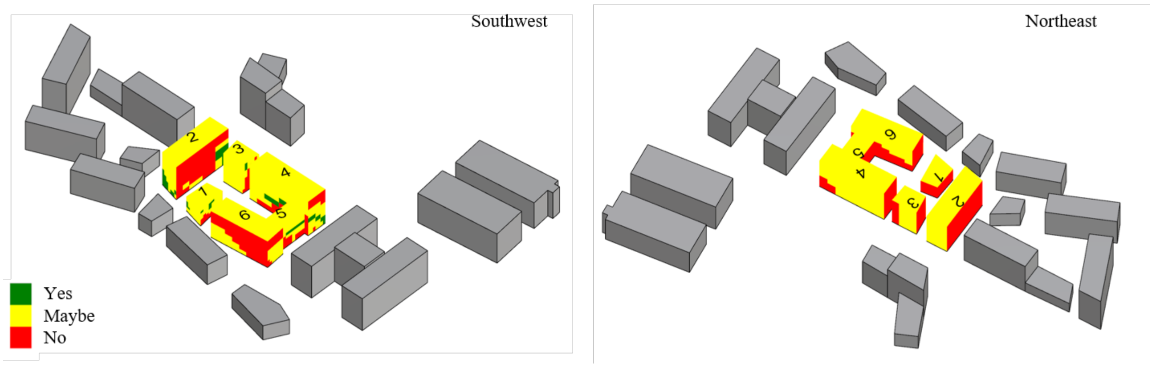


Figure 5-3 The results after the first iteration, where the picture to the left shows the area in the south-west direction and the results for the north-east direction to the right.

It is clear that the amount of glass have affected the design for the surfaces in the south direction that have turned into red areas. The increased area of glass both affect the daylight availability into the room and the solar heat load, where both metrics have increased which will affect the total aggregation of the result. Since the sunlight hours are dependent on the location of the building, i.e. sun position and surrounding obstructions, the metric cannot be adjusted in this stage of design. The red areas for the façades that are facing north will always be red due to that the sunlight hours never reach the requirement. This parameter is important to bear in mind during the design, a parameter that often is neglected. The adjustments to the design also affected the thermal transmittance, visualised on the roof, which has increased for all buildings, compared to previous simulation. For further evaluation, results for the DF_{median} and the solar heat load, aggregated separately can be found in Appendix E.

Final iteration

To further improve the results, other type of shadings and glass properties have been enhanced as well as the thermal transmittance for each construction element has been assessed. Figure 5-4, shows the results for the second iteration where internal shadings have been replaced with intermediate shadings, an energy coating is added improving the glass properties and the thermal transmittances for each construction element have been improved. Complete input data can be found in Appendix E.

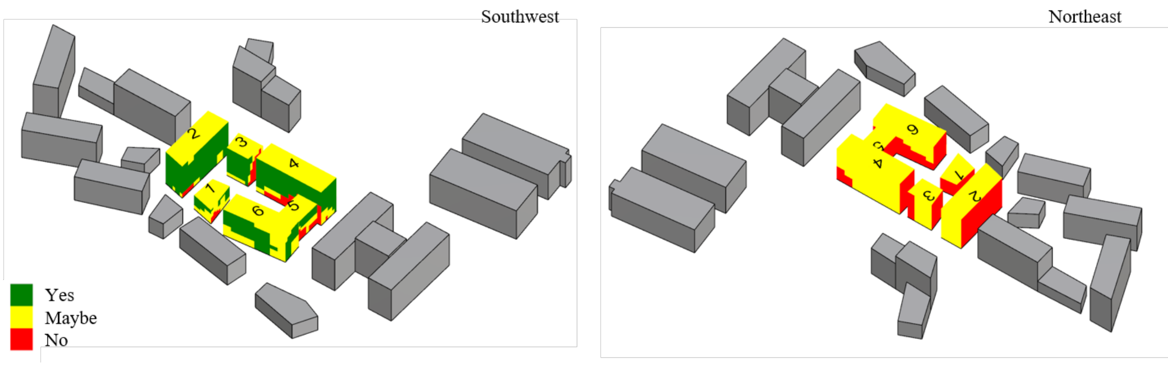


Figure 5-4 Total aggregated results for the second iteration where improvements concerning the shading and glass properties as well as the U_m-value have been made.

As the figure shows, the results for the southwest direction have been improved where the solar heat load has decreased, which turned out to be the challenging metric for this case. For the northeast direction, the sunlight hours are unaffected and therefore so are the results for the façades facing this cardinal direction. As mentioned in Section 3.1, there are ways to handle this issue, but the architect in charge need to be aware of the situation. The U_m-values of the buildings are still in the interval of maybe and could be further improved.

5.1.4 Analysis of result

This case study has shown how the simulation methodology can be utilised in the early stages of design in order to find a design solution, which indicates satisfying levels of sun- and daylight. By calculating the U_m-value, an initial indication about the energy performance of the building could also be achieved. The totally summed values of aggregation, which are the combination of metrics with regard to sun- and daylight, have been evaluated. This presentation of results could highlight troublesome areas of the design that could be avoided.

The result of the case study showed small improvement for each iteration and of course, the building design could be further improved. One could also think about the simplifications in the model and what effect that would have on the results. The tilted walls or roofs in the blueprint are not included in the model, which will have a small negative affect on the daylight availability on the opposite side of that building, although it is on the safe side. The room depth was also assumed based on reasonable values, but would affect the solar heat load in the simulations. As stated in the report, due to model limitations building four, five and six have wall surfaces, which are doubled and include windows, which will increase the U_m-value of each building.

The shading factor and glass coatings can be added in order to evaluate if the level for solar heat load is possible to reach. It should be stated that for the daylight availability the light transmittance has been considered. Though, since the purpose of this methodology is to give an indicating value, and also since the correlation is based on calculated data where such a factor could already be included, this factor is neglected.

The simulations were performed stepwise where input data was adjusted in order to rerun the simulations. This process was quite time consuming due to the solar radiation analysis. In order to run the simulation the mesh was limited to a coarser setting, which lead to large grid distribution and several areas were still red or yellow, even after two iterations. By improving the simulation time and enable finer mesh settings, the result might show a slightly better outcome.

What should be highlighted is that for this residential area, the main problems concern the courtyard and the distances between the buildings, which could not be improved in this project. A main contributor to the red areas were also the sunlight hours in the north direction, which was the intention to visualise in order to keep in mind when designing, not to forget the requirement for that metric in later design stages. Even though this case study was limited to only change parameters concerning the building characteristics, the methodology works for different stages of the building development. This is a strength of the methodology and could have a great impact on the construction business in the long run.

5.2 Verification of established correlation

The aim of this case study is to evaluate and verify the established correlation between the DF_{median} and the SVF, described in Section 4.2. By the means of simulating the DF_{median} for a case study where calculation DF_{point}-values exist from the software Mental Ray 3D Max, these can be compared and the preciseness of the correlation can be established. The DF_{median} has been simulated for the lower parts of the building in order to be comparable to the precalculated values used in the comparison.

5.2.1 Case study 2 – Project X

This is a project located in a district where a plan for a new area is under investigation, which will include both residential buildings and several businesses. Today, it is a parking lot but after completing the construction, it is planned to be an urban area with a mix of modern buildings in the city. 2D drawings and daylight calculations have been provided for this case study, but due to confidentiality reasons, the information about this project is limited, therefore it will be called project X. Figure 5-5, shows the 3D model of the building along with a layout for the first floor.

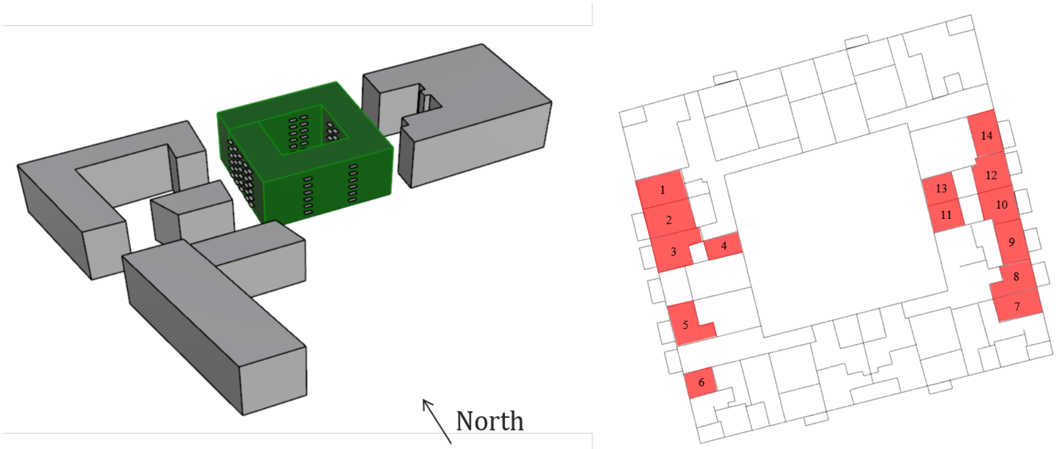


Figure 5-5 The 3D model of the simulated building (to the left) where the green building has been investigated. To the right, the floor plan layout includes each investigated room numbered to provide an easy way of comparing the results.

5.2.2 Simulation conditions

According to Figure 5-5, the green building will be evaluated with regard to the DF_{median}. The geometrical conditions are presented in Table 5-3. The building height and number of floors are set according to the drawings provided. The top floor of the building has been simplified due to methodology limitations, which resulted in equal floor heights throughout the building. The number of façades in the model is ten, this is to be able to create a courtyard in accordance with the methodology's limitations, which makes two of the façade surfaces hidden in the wall resulting in eight visible surfaces. Since the input parameter allows one glass ratio per building, the GFR is a calculated mean value. The layout and placement of the balconies has been simplified, so that each balcony start at the second floor and will shade the apartment on the first floor, which differ from the blueprint.

Table 5-3 The input data for the second case study where the DF_{median} has been simulated. The table only include the parameters, which affect the daylight calculations using the developed correlation.

Geometrical parameters	
Height [m]	21.5
Number of floors	7
Number of façades	10
$A_{glass}/A_{room.floor}$ [-]	0.17
Room depth [m]	4.0

Since the purpose of this case study is to evaluate the correctness of the established methodology and to compare the distinguished correlation against calculated data, the mesh in the model have been chosen to a fine mesh setting. The grid size is therefore equally distributed over each façade, which will simplify the comparison of specific point values in the simulation.

5.2.3 Simulation results

The whole building has first been simulated with regard to the DF_{median}, both as real values and as aggregated results. Figure 5-6, shows the actual result from the daylight simulation, which indicates that there are areas, which do not meet the requirement of the DF and would need further improvement. These areas are the colours below a DF of 1.0 %. Results from other cardinal directions are presented in Appendix F.

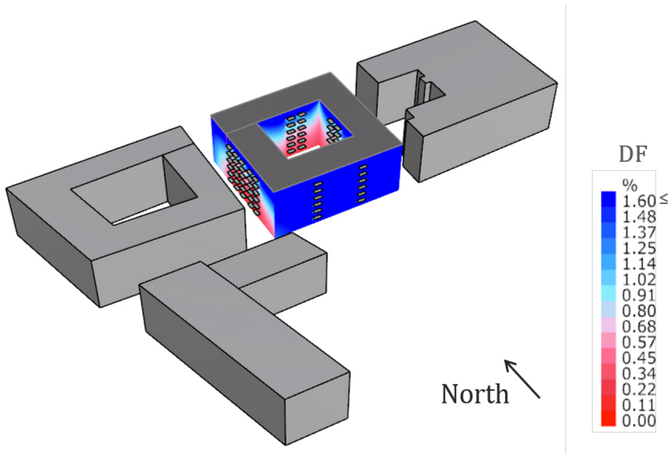


Figure 5-6 The figure shows the results of the daylight simulation for case study 2 where the distribution of the DF_{median} is presented.

Figure 5-6, showed the distribution of the simulated values of the DF_{median}, which gives a good overview of the results. To compare the results, it was necessary to find a point of evaluation where the values for the simulated DF_{median} could be extracted. Since the simulation in the developed methodology is based on the value of the SVF which is transformed for the surface of a window into the room, the point of evaluation was chosen at a height in the middle of a representative window.

The representative height was chosen as a point in the grid, 1.5 meter from the floor. For the points in the grid, located close to the position of the precalculated data (see Figure 5-7), the result of the DF_{median} was extracted. Whereas for the precalculated results, the valid point is according to the Swedish Standard SS 91 42 01 at a height of 0.8 meters from the floor.

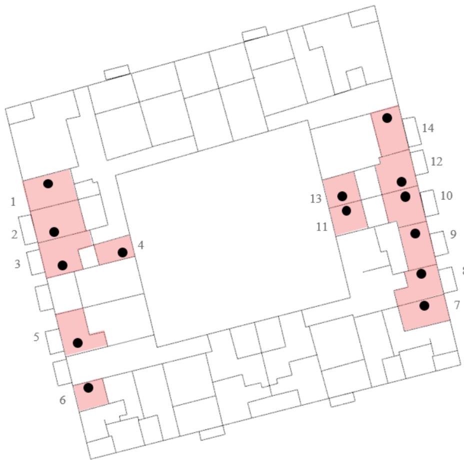


Figure 5-7 A principal sketch of the floor plan layout where the DF_{median} for the red areas has been extracted, from the developed methodology. The black spots marks the points where the precalculated results of the DF_{point} exists.

In Table 5-4, the results from the case study are presented. The table includes the areas of the floors and windows according to drawings, the window-to-floor ratio for each room and the results for the precalculated Daylight Factor ($DF_{measured}$) and the simulated results from the developed methodology (DF_{method}). Furthermore the difference between the two calculations is presented in percentage in the table. Note that the simulated results are based on a mean value of the window-to-floor ratio (see Table 5-3) which is assumed to be a ratio of glass to floor ratio inserted as input in the developed methodology. Whereas the calculated results are based on one ratio of window-to-floor per calculated room.

Table 5-4 Results and comparison of actual calculations and the simulated DF. The actual calculation for each room is summarized in $DF_{measured}$ and the simulated result in DF_{method}.

Room ID	Room type	Afloor [m^2]	Awindow [m^2]	Awindow/Afloor [%]	DFmeasured [%]	DFmethod [%]	Difference [percentage]
1	Living room	25.1	4.2	16.9	0.4	0.65	0.25
2	Kitchen	14.5	3.4	17.8	0.5	0.42	-0.08
3	Living room/Kitchen	26.6	4.5	14.4	0.3	0.37	0.07
4	Bedroom	11	1.4	12.9	0.2	0.46	0.26
5	Living room/Kitchen	23.8	4.8	16.9	0.2	0.39	0.19
6	Bedroom	13.3	2.8	21.3	0.6	0.62	0.02
7	Bedroom	13.3	2.8	21.3	0.6	0.60	0
8	Living room/Kitchen	18.8	3.4	14.5	0.6	0.3	-0.3
9	Living room	19.9	4.2	21.3	0.5	0.39	-0.11
10	Living room	21.2	2.8	13.3	0.2	0.60	0.4
11	Kitchen	15.7	3	19.4	0.3	0.21	-0.09
12	Living room	21.2	2.8	13.3	0.5	0.60	0.1
13	Kitchen	14.1	3	20.6	0.4	0.32	-0.08
14	Living room	20	4.2	21.2	0.4	0.39	-0.01

The results of the comparison is also summarised in a bar chart where the calculated results from Mental Ray are normalised to 1, see Figure 5-8. Conclusions from the comparison can easily be drawn about the difference of the simulated results from the developed methodology and the precalculated results. A general conclusion is that for most of the cases, the results from the methodology are close or lower than the pre-calculated values in Mental Ray, indicating that the developed methodology is on the safe side.

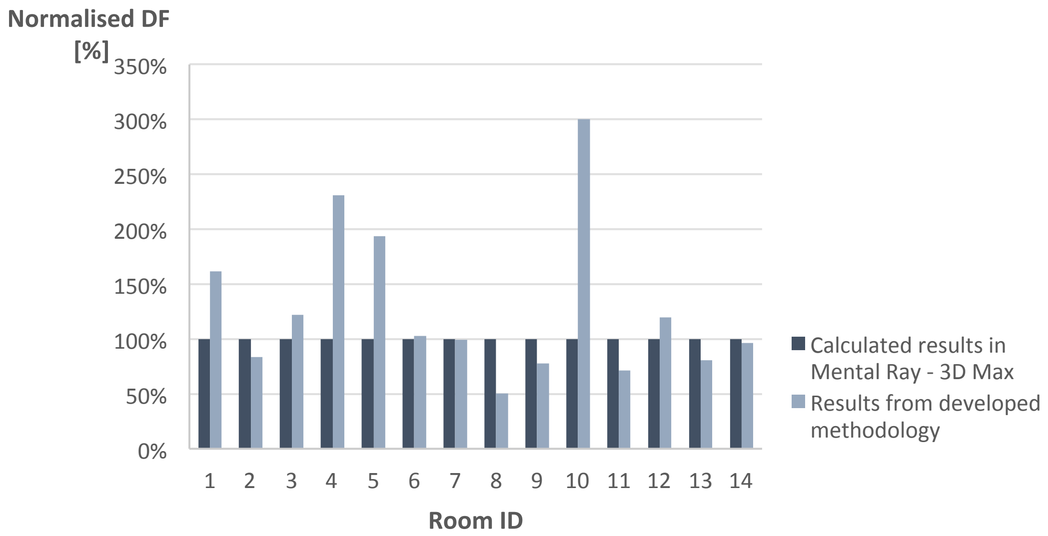


Figure 5-8 The comparison of the simulated results from the developed methodology to the precalculated results in the software Mental Ray. The dark blue bars are normalised values for the precalculated results of the DF_{point}. The light blue bars are predicted values relative to the results from Mental Ray, indicating if the result from the methodology would be higher or lower than the precalculated result.

The rooms that stand out the most are room number 8, 4 and 10. Room number 8 seems to have a DF twice as high for the precalculated value compared to the developed methodology, which could be caused by the difference in calculation methods and the position of the evaluated point. The results obtained by the developed methodology are lower than the actual calculation, which would result in a best-case scenario.

On the other hand, for room number 4 and 10, the predicted DF from the developed methodology is more than 100 percent higher than the performed calculation. The consequence would be that this result could be better than in reality. The difference in percentage, see Table 5-4, is 0.26 and 0.4 respectively which could be regarded as a larger difference, but still all values are below one percent, not meeting the requirement of the Swedish building regulations. In Appendix F the results of actual values instead of normalised values are presented.

In this case study, four out of fourteen rooms are much higher for the methodology-based results than the precalculated, though it should be noted that these are differences for DFs below 1.0 % with several simplifications. Furthermore, another reason for the deviation in the results could be due to that eight out of fourteen simulated rooms in the developed methodology contain balconies, a consequence of the modelling structure, which is not included in the blueprints and neither in the precalculated values. In Appendix E, the result of actual values instead of normalised values is presented.

5.2.4 Possible sources of errors

Due to limitations in the developed methodology and the restricted amount of data available for this case study, there are several possible sources of errors. The inaccuracies could either affect the result in a positive or a negative way, but should be kept in mind when comparing the results.

Since the case study input data was limited there are many uncertainties concerning geometries in the model. The geometry created with this methodology is simplified; both surroundings and the evaluated surfaces are made as simple boxes. The balconies are not added correctly, since they start at different levels than according to the blueprints, which was not possible to model during the simulations. This caused larger variations for the rooms with balconies (8 out of 14 rooms), since the balconies act as shading objects, which decreased the simulated DF_{median}. Due to the limited information about the calculation process made in Mental Ray 3D Max, there are also uncertainties about the procedure of the calculations. This includes how geometries were modelled and which surroundings that have been included, resulting in that differences might occur from the way it has been defined in the methodology since simplifications have been made.

The pre-calculated data for this case study was performed in a software based on backward ray-tracing, similar to ours, but the main difference concerns the point of measurement for the results. The precalculated data is measured according to BBR, whereas the point of measurement for the simulated values is at a point of an assumed window in the façade. This is due to that the methodology uses a correlation based on the SVF while the precalculated results are measured in a certain point inside an actual room.

The available results for comparison only included rooms, which did not fulfil the minimum requirements of the DF according to BBR. The requirements according to BBR are set for DF_{median} in a point but the methodology is based on the median value of the DF, which might increase the deviation.

6 Conclusion

This Master thesis work concludes that by implementing simulation methodology in early stages of design, conditions for a new building development can be set based on the prerequisites on site. Since no existing evaluation methods are adapted to these early stages, the purpose of this Master's thesis was to achieve methodology that would facilitate the design process for architects, city planners and engineers. Issues of a design can be addressed early during the planning phase of building developments for the purpose of achieving a good daylight comfort, e.g. a more sustainable densification of urban areas, as well as a good energy performance of the building.

The developed methodology have been determined as functioning and operates in accordance to the purpose. It provides results accurate enough to base decisions upon despite the simplifications with regard to geometry and simulation inputs. Throughout the case studies the strength of the method is presented. In order to completely verify the developed methodology and the distinguished linear regression between the DF_{median} and the SVF, several case studies with exact calculation results should be performed. Simulations based on different software may differ and therefore, a complete verification should include a comparison of measured data and results from different of software.

Since the methodology is developed for early design evaluations, where required input data to perform detailed energy and daylight simulation does not exist, for some buildings there could be a built-in error. Therefore a margin of error has been added to the aggregation of results, which rather fails a building than approves it with regard to the four metrics. Even though there still is room for improvement and a validation of the methodology, as a first step in verifying the methodology, the results of the case studies are satisfying.

7 Future Development

In this early stage of the development of this methodology, there are several areas that can be improved. In the following chapter, potential future improvements that have appeared during the thesis work will be explained.

The regression analysis of the DF_{median} and the exterior metrics can be further improved. The provided database has exclusively been used for the development of the correlation, thus there could be additional exterior metrics that correlates better to the DF_{median}. The first exterior metric that comes to mind, not included in the database, is the Vertical Sky Component (VSC). The VSC is based on the majority of the parameters that the DF is, the exterior metric that is most similar to DF and would be interesting to evaluate. Another aspect of development of the correlation is to divide it into intervals with different correlations depending on the type of building or the building properties, e.g construction year, type of glazing etc. This would make the correlation more accurate and applicable to existing buildings when evaluating the consequences of the densification.

Regarding the simulations, the simulation time is for now not optimal. When evaluating case study one, with a medium accuracy consisting of 1200 grid points, the time of simulation was 35 minutes. To develop an area in an iterative way, this is considered to be too long. The solar irradiance analysis is the time consuming simulation since it calculates annual data for each point in the grid per hour of the year. Other simplified simulation procedures have been evaluated, but none, which gives an accurate response, has been found. In order for the methodology to operate as desired, the simulation time should be limited to approximately five minutes.

The energy performance of the building is evaluated by the U_m-value, which is an early indication. For future improvements, the energy use of the building could be included which would be of interest especially for the owner of the property. In that case, a fictive room could be implemented by the Autozoner algorithm (see section 2.1), which connected to a simulation engine, calculates the energy use of each building.

Another potential area of development of the methodology concerns the intelligence of modelling. By importing completed 3D models of a building area, the surfaces could be automatically grouped according to the building properties, e.g. wall, roof or foundation. Additionally, if the type of activity can be determined a wider use of the methodology can be applied.

In order to verify the correlation and also validate the methodology, more case studies should be performed. This could be done in several ways, either by using an existing building where measurements are possible to perform or by comparing daylight calculations performed for both approved and non-approved rooms to the simulated values. A comparison should be made with more than one simulation tool since there can be differences between the tools on the market today due to their different kinds of approaches when simulating daylight availability which could affect the results.

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9 Appendices

Appendix A – Workflow description of regression analysis of DF_{median}

Appendix B – Workflow description of geometry relation

Appendix C – Supplementary material of methodology description

Appendix D – User manual for developed methodology

Appendix E – Supplementary material from case study 1 - Lindholmshamnen

Appendix F – Supplementary results from case study 2 – Project X

Appendix A – Workflow description of regression analysis of DF_{median}

This chapter will describe the steps and results of the regression analysis of DF_{median} and exterior metrics.

Data management

A database has been used containing data from over 100 buildings in Sweden with approximately 25,000 rooms, both simulated and calculated. A part of the data has been prepared by Bengt Dahlgren and is based on buildings situated in Gothenburg, which have been manually modelled in a CAD environment and simulated using Grasshopper along with additional plugins. The majority of the database, modelled by other parties, is based on a Grasshopper script which automatically calculates and simulates the metrics of interest based on imported 3D models of the buildings.

The primary intention was to use as much data as possible from the database in order to achieve a solid base for the correlation. After the database was examined a data frame was set in order to achieve reliable data where tracking of the actual results were possible. The data frame was set based on the final criteria presented in Table 1. The filtering was performed with a Python script to finally achieve the size of approximately 500 rooms. For each iteration a trend line has been fitted to the results. The coefficient of determination, R^2, was calculated for all correlations evaluated and defines how well the line fits the data.

Table 1 Final filtering parameters for data management of the database.

Filter	***Description***
The data is provided by Bengt Dahlgren AB	Since the calculations and simulations have been performed in-house, they are accessible.
Only residential buildings	These are not as complex as commercial buildings regarding the building envelope and indoor activity. Due to the different kind of layouts and requirements, the data that the correlation is based on might scatter and lose reliability.
Only rooms with a well-defined measuring point	The room has a point possible to identify directly or by an analysis of several points.
The simulation should be performed as type 1	The conditions for simulation type 1 are based on optical conditions including reflectance, transmittance, certain settings for calculation software, ambient bounces and size of computational grid. The conditions can be found in (Eriksson & Waldenström, 2016)

Method of investigation

The interior metric was chosen as the DF_{median}, as mentioned in Section 3.2.1. Together with the best correlating exterior metric, SVF or SEF, a relation was set. The correlation between the Daylight Factor and the exterior metrics has been investigated iteratively. It was established quite early in the process that the area corresponding to each value for the metric would have a great impact on the final correlation. The goal of at least 0.8 was set for the coefficient of determination, which indicates that the relation of the dataset and trend line agrees up to 80 percent.

Results

From the first iteration it turned out that the data was too scattered and showed no correlations for any of the metrics investigated. As shown in Figure 1, the correlation of the DF_{median} and SVF is poor and the data is widely spread. The same results were obtained for the sky exposure factor (SEF).

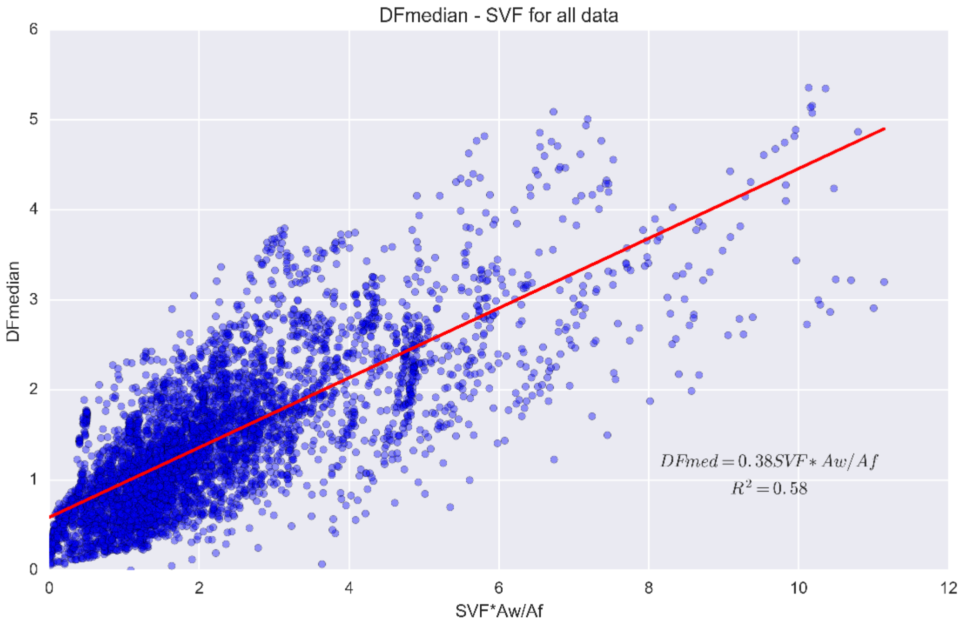


Figure 1 Correlation of DFmedian and SVF for all residential buildings in the database.

In order to find an accurate and valid correlation, data based on known modelling and calculations was desired. The data was thereby limited to only include results from Bengt Dahlgren performed in a Master's thesis from 2016. The following part of the results is therefore only based on this selected data. In the dataset eight residential buildings are included, due to inconsistency for building eight it was removed.

Figure 2, shows how the SEF correlates to the median DF in the room. The dataset is slightly scattered but still correlates enough to the linear trend line. The correlation factor reaches and exceeds 0.8, which was considered sufficient for the purpose of the study.

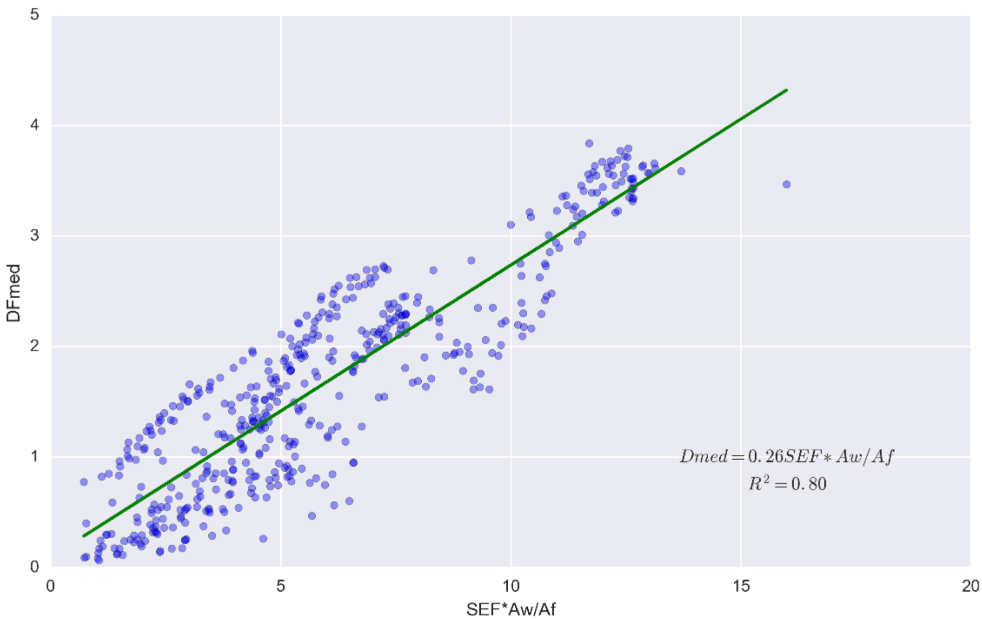


Figure 2 Correlation between DFmedian and SEF for building 1-7.

If comparing the result in the figure above with the results for the SVF according to Figure 3, one can see that there is a stronger correlation between DFmedian and the SVF, even though they do not differ that much. The darker points in the graph represent a larger amount of rooms. If comparing the amount of darks spots, they tend to follow a more gathered trend for the SVF. Therefore it was chosen as the exterior metric for the correlation.

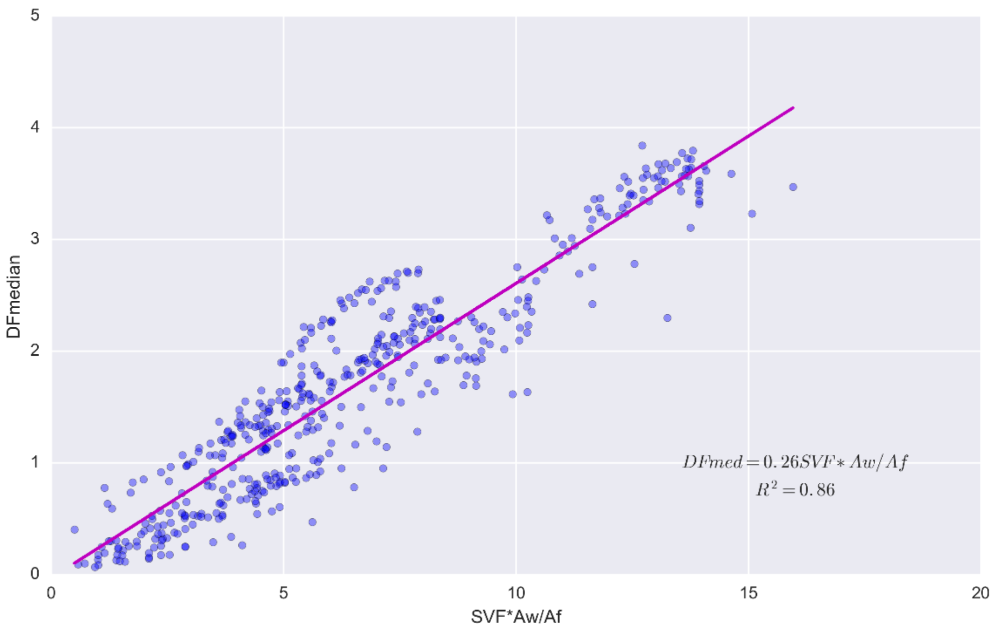


Figure 3 Correlation between DFmedian and SVF for building 1-7.

Since a part of the purpose of this thesis was focused on finding a correlation which can lead to an indication whether a building could meet the requirement of daylight, an important aspect was that the correlation had a strong foundation in the lower bound of the DF_{median} interval. The correlation need to satisfy the following domain:

$$0 < DF_{median} < 1.2$$

When DFmedian is above 1.2 the requirements according to BBR is fulfilled, this includes a margin of error since the actual limit is 1.0. For values below 1.2, it is interesting to be able to evaluate what changes can be done in the project in order to improve the daylight factor and in that sense also confirm that the regulations has been met.

In order to confirm that the relation is applicable for all buildings in the study, Figure 4 shows the results for all buildings modelled by Bengt Dahlgren where each building has its own colour. The figure shows that for each building there is a linear correlation, however some parts of the data deviate from the trend line.

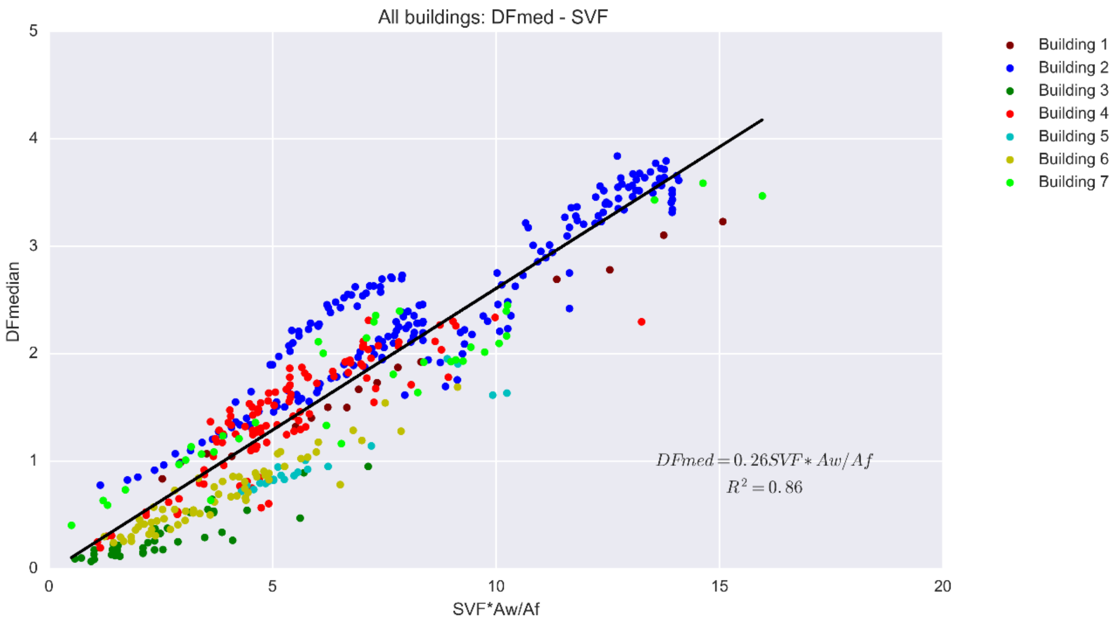


Figure 4 *Correlation of DFmedian and SVF for buildings simulated by Bengt Dahlgren. The figure shows how each investigated building correlates to the global established equation*

The final equation for the regression analysis used in the developed methodology through this thesis work is:

$$DF_{median} = 0.26\,SVF\ x\ \frac{A_w}{A_f}$$

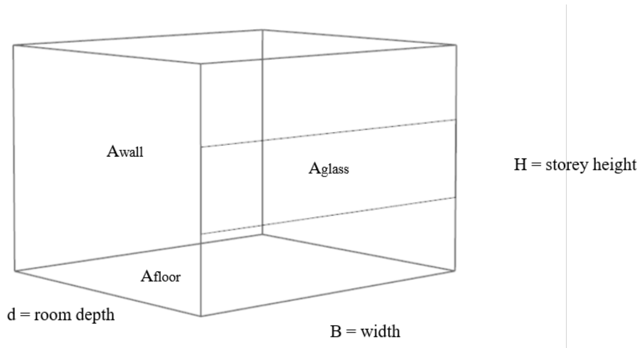
The correlation factor between the global equation and the Daylight Factor results for each building have been calculated and summarised in Table 2. The factor tells us how well the local and global equation correlates. For all buildings, the correlation factor was satisfying.

Table 2 Presents the correlation of each buildings local equation to the global correlation.

Building ID	**Local equation**	**Correlation to global equation**
1	$y = 0{,}20\ x\ SVF\ x\ \frac{A_{glass}}{A_{floor}} + 0{,}29$	0.99
2	$y = 0{,}22\ x\ SVF\ x\ \frac{A_{glass}}{A_{floor}} + 0{,}55$	0.87
3	$y = 0{,}13\ x\ SVF\ x\ \frac{A_{glass}}{A_{floor}} - 0{,}03$	0.78
4	$y = 0{,}23\ x\ SVF\ x\ \frac{A_{glass}}{A_{floor}} + 0{,}19$	0.75
5	$y = 0{,}20\ x\ SVF\ x\ \frac{A_{glass}}{A_{floor}} - 0{,}14$	0.887
6	$y = 0{,}18\ x\ SVF\ x\ \frac{A_{glass}}{A_{floor}}$	0.898
7	$y = 0{,}2\ x\ SVF\ x\ \frac{A_{glass}}{A_{floor}} + 0{,}37$	0.877

Appendix B – Workflow description of geometry relation

This appendix shows the steps of deriving the relation between $\frac{A_{glass}}{A_{floor}}$ and $\frac{A_{glass}}{A_{wall}}$.



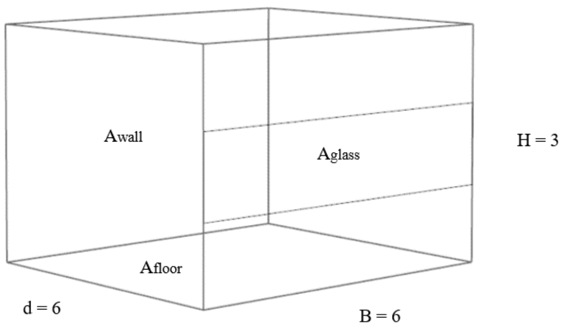
$$\frac{A_{glass}}{A_{floor}} = \frac{A_{glass}}{B\ x\ d}\ (1) \quad \rightarrow \quad B = \frac{A_{glass}}{\left(\frac{A_{glass}}{A_{floor}}\ x\ d\right)}\ (2)$$

$$\frac{A_{glass}}{A_{wall}} = \frac{A_{glass}}{B\ x\ H}\ (3)$$

(2) Inserted in (3) →

$$\frac{A_{glass}}{A_{wall}} = \frac{A_{glass}}{\frac{A_{glass}}{\left(\frac{A_{glass}}{A_{floor}}\ x\ d\right)}\ x\ H}\ (4) \quad \rightarrow \quad \frac{A_{glass}}{A_{ext.wall}} = \frac{A_{glass}}{A_{floor}}\ x\ \frac{d}{H}\ (5)$$

Test to verify equation 5



By assuming the following: $\frac{A_{glass}}{A_{ext.wall}} = \frac{1}{3}$, d = 6m , B = 6m and H = 3m and using eq. (3) and (1):

(3) → $A_{glass} = \frac{A_{glass}}{A_{ext.wall}}\ x\ (B\ x\ H) = \frac{1}{3}\ x\ (6\ x\ 3) = 6$ m^2

(1) → $\frac{A_{glass}}{A_{floor}} = \frac{6}{6\ x\ 6} = \frac{1}{6}$

(5) Inverted → $\frac{A_{glass}}{A_{floor}} = \frac{A_{glass}}{A_{ext.wall}}\ x\ \frac{H}{d} = \frac{1}{3}\ x\ \frac{3}{6} = \frac{1}{6} = \frac{A_{glass}}{A_{floor}}$ according to above.

Appendix C - Supplementary material of methodology description

To be able to aggregate the results of the simulations and calculations, threshold values have been used. Regarding the sunlight hours and U_m-value, the limits are not specified in Swedish building regulations. These values were set in consideration with experienced professionals along with publications by Boverket (see Chapter 3). Table 1, presents the aggregation limits for the sunlight hours and thermal transmittance. Table 2, the thresholds for silver according to Miljöbyggnad and Table 3, the limits to reach gold. Since it is only the Daylight Factor and the Solar Heat Load that is changing, only these values are presented.

Table 1 Limits set for aggregation of the different metrics for sunlight hours and mean U_m-value.

Limits for aggregation	***Yes***	***Maybe***	***No***
Sunlit hours [h]	>4	2.5 – 4	< 2.5
Mean U-value [W/m^{2}K]	<0.3	0.3 – 0.45	> 0.45

Table 2 The limits of aggregation for Miljöbyggnad Silver for Daylight Factor and Solar Heat Load.

Silver	***Yes***	***Maybe***	***No***
Daylight Factor [%]	>1.3	1.0 – 1.3	< 1.0
Solar Heat Load [W/m^2]	<27	27 - 31	> 31

Table 3 The limits of aggregation for Miljöbyggnad Gold for Daylight Factor and Solar Heat Load.

Gold	***Yes***	***Maybe***	***No***
Daylight Factor [%]	>1.3	1.0 – 1.3	< 1.0
Solar Heat Load [W/m^2]	<16	16 - 20	> 20

When calculating the predicted solar heat load for each point in the grid, the following estimations of shading factors and glass coatings were used[1] (see Table 4 and Table 5).

Table 4 The g-values for different types of shadings.

Shading type	$g_{shading}$
Exterior	0.2
Intermediate	0.5
Interior	0.7
None	1

Table 5 The g-values for different glass types.

Glass type	g_{glass}
Clear glass	0.7
Energy coating	0.55
Clear solar coating	0.35
Dark solar coating	0.26

[1] In agreement with Max Tillberg, Bengt Dahlgren AB.

Appendix D - User manual for developed methodology
This document has been written in order to provide guidance as a manual for the methodology made in Rhinoceros and Grasshopper. Snapshots will be presented explaining what some of the steps' purpose are. This along with a step-by-step guide is a support for the user if there are any uncertainties to be able to get results and indications out of the methodology.

1. Input data

The following steps are necessary for the analysis to run and to get the results desired. It has been divided into different steps to be as clear as possible. The Grasshopper file is open to adjustments and can be modified by the user, for example by adding simulation objects, increase the domains of input parameters or changing simulation settings.

Simulation objects

By drawing polylines right into the Rhino scene analysis objects can be defined. The footprint of each building is drawn and in Grasshopper the building gets defined. Right click on 'Building polyline' and press 'Set one curve' and pick the desired polyline in Rhino, afterwards press enter. The same goes for the balconies, draw a polyline in Rhino and define it by the same manners in Grasshopper. On the number slider below the 'Balconies' box the starting floor of the balconies can be set.

Furthermore the additional parameters for each object is set by adjusting the number sliders or by choosing a suitable number in the dropdown lists for the different parameters. At the bottom of the input data group there is a panel showing a part of the results. In this panel parameters depending on the input data are presented, the interface is shown in Figure 1. When it comes to the quotient of Area window over Area room floor the slider goes from 0 to 1. However, the actual quotient used is limited to when the quotient of Area window over Area exterior wall reaches 1.

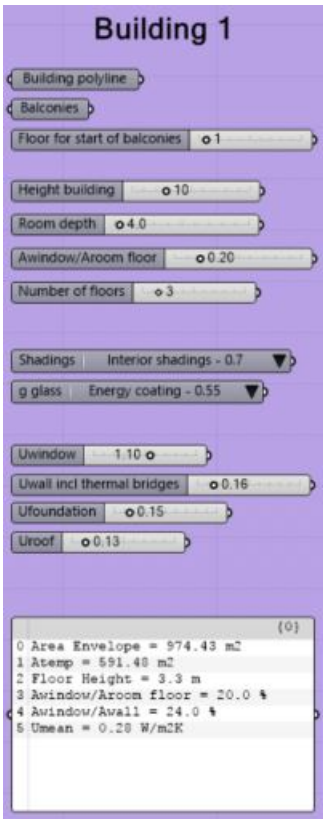


Figure 1 Input data for each simulation object.

For now six simulation objects are added to the methodology. More objects can be added just by copying the whole group and draw all the wires to each group, see Figure 2. By zooming in the boxes plus and minus signs pops up. Press the plus sign at the bottom to add an input parameter.

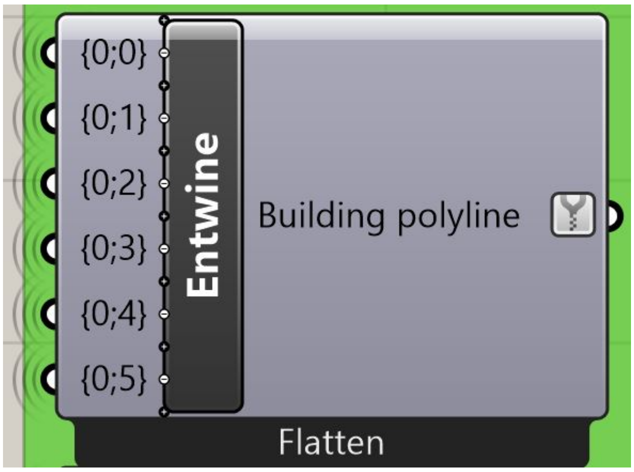


Figure 2 Boxes gathering the different parameters for each simulation object and put into lists.

Simulation settings

The next group of input data consists of analysis options. First a desired grid size is chosen. The maximum length of the edges in the grid is determined in meters. If a finer distribution of the results is desired the length must be decreased. The next step is to decide which grade of Miljöbyggnad to strive for, this choice affects the aggregation of the final results and how they will be grouped.

Surrounding objects

Surrounding objects such as buildings, trees or monuments can be added to the simulation almost in the same way as buildings to be analysed. Define a polyline drawn in Rhino to Grasshopper and add a height. The height is added as a point in the Rhino model with its z-coordinate. It can either be defined in Rhino by right clicking on 'Pt' and chose 'Set one Point' or by changing the z-coordinate manually by clicking 'Manage Point collection'. The way the surroundings are constructed can be seen in Figure 3.

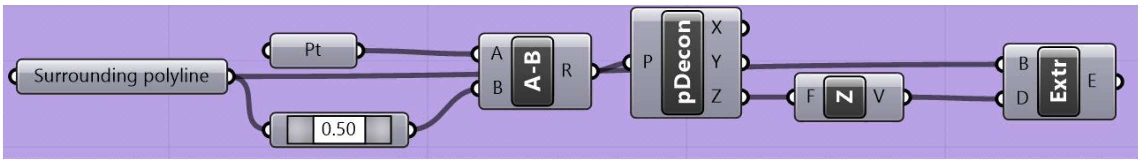


Figure 3 The construction of surrounding objects. A footprint of the object is defined and the objects gets extruded along the z-axis.

More surrounding objects can also be added to the simulation. Mark the same boxes as in Figure and copy them. Pull the wire from 'E' in 'Extr' to the gathering surrounding box, hold Shift and release it.

In order to add a ground, just right click on the 'Ground' box and press 'Set one rectangle' to add a ground surface in the Rhino scene.

Weather data

To be able to run climate-based simulations, i.e. for Sunlight hours or Solar heat load, a weather file is needed. These are called epw-files and can be found for suitable locations at the Energy Plus webpage, https://energyplus.net/weather, for this thesis the file with data from Gothenburg has been used. By changing the Boolean toggle from False to True the epw-file can be chosen locally from the computer.

Simulation

After the steps above are performed the simulations can be run to get the results from the methodology. Switch the Boolean toggles from False to True in order to run the simulations for each indicator. The mean U-value is calculated based on U-values for each construction element and their area, it is therefore not a simulation that needs to be run it is solved by simple calculations. If working in an iterative way the authors suggest to first run the simulations for the Daylight Factor and Sunlight hours first and run the Solar heat load when a desired design is achieved as a final check. This is due to that it is a time consuming simulation.

Preview

In this step geometries and results can be shown or hidden directly in the model. In the check lists the elements that is going to be shown can be marked. In the drop down lists below one result at the time can be shown as a colour mapped result on the facades or for the mean U-value, on the roof. In order to not get blurry results the roof, facades and windows needs to be hidden from the preview list of the analysed geometries.

Saving results

The last group placed in the input data is the option of saving results right into Rhino. By changing the Boolean toggle from False to True each of the elements or result gets saved as a layer in the Rhino model and can from there be shown or hidden. The benefit of this option is that when the layer has been saved or imported to Rhino the Rhino model can be saved and opened at another occasion. If not saving the layers the simulations has to be rerun to be able to see the results again.

2. Constructing necessary simulation conditions

This part is about how the simulation conditions are built up in Grasshopper with the inserted input data. Again the user can do changes but it is made to just run, what is done in each stage or group is here explained.

Creating lists of input data

For each parameter the data structure, or the data tree, is trimmed down. Based on which simulation objects that are added to the methodology the other parameters are erased from the tree structure so only the added buildings with its characteristics are used in the lists, see Figure 4.

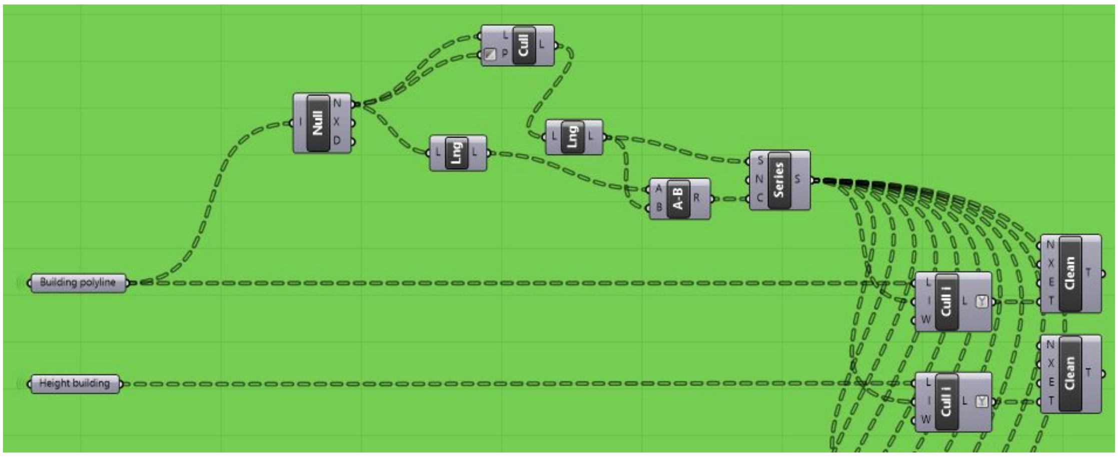


Figure 4 Sorting the input data lists based on which Building polylines that are defined.

Creating a 3D environment

Since all everything inserted into Rhino is based on 2D this far a 3D environment is needed. From the 2D polylines the 3D objects are created by extruding along the z-axis based on heights inserted in the input data section. Balconies added to the analysed objects are surfaces shading the facades and affecting the simulated results. They are added depending on which floor they start at in an array which means that they start at one floor and goes from there to the top and are added by the same manner for a whole building and is for that reason not that flexible.

The correlation between the Area window over Area room floor and Area window over Area exterior wall has been used in order to get a value of the total window area and how it is related to the area of exterior wall. A condition of limiting the Area window over Area room floor has been set which has been made so both the quotients can have a maximum value of 1. Even if a larger value can be inserted for the Area window over Area room floor the maximum value will be used for the calculation and simulations further on in the methodology.

Analysis grids and calculating areas

When the geometries has been built analysis grids can be put on the surfaces of interest. The main part for the simulations is the construction of the analysis grid for the facades. It is simply built with the surfaces corresponding to the facades with a maximum length of the edges for the grid inserted in the input data stage. The output of this group is both grids and the number of grid points, which can be shown in the Rhino model if right clicking and press ‘ Preview’. Grids for the roofs are also created. These are just for the visualisation of the mean U-values and do not affect the simulations. To be able to later on perform the calculations of the mean U-value the areas of each construction element are done in this stage as well.

Visualisation and Preview

Presenting the results and geometries in an easy way was a part of the purpose when constructing this methodology. In this stage the different parts that wants to be shown are put together and can be shown or hidden in the Rhino model by clicking in the input data lists.

Baking results and geometries

This step is also controlled in the input data stage. Through the Boolean toggles one can decide whether the results or geometries should be saved in layers in Rhino. As mentioned earlier the benefit of this is that the results are saved and does not have to be rerun in order to see them.

Gathered characteristics

In order to show some of the results that are interesting but not really important for the simulations to be run are in this stage gathered as lists for each building. These results are presented for each building in the input data in a panel and depend on the input data inserted.

3. Simulations and calculations

With Grasshopper boxes along with Ladybug and Honeybee components the simulations and calculations are performed. The different metrics has been simulated or calculated separately and will go further into detail below.

Daylight Factor

The Daylight Factor has been calculated by combining a simulation of the Sky View Factor and the found linear regression. The simulation is based on a Ladybug component and the results get managed afterwards in order to be presented in a suitable tree structure. The results are simply put into the linear regression and an answer of the Daylight Factor is achieved.

Sunlight Hours

In order to get results of the Sunlight hours in each grid point a location dependent analysis is performed. This is made with Ladybug components with the epw-file connected to them. A sunpath is created and the number of Sunlight hours is simulated at vernal equinox.

Solar Heat Load

To achieve results of the Solar Heat Load the solar irradiance in each grid point is required. This is a time consuming step of the simulations since it is simulating results for each hour of the year in each grid point which makes the lists of data unnecessary long since the maximum value of solar irradiance is the only needed value. The results of the solar irradiance simulation is afterwards put into simple calculations of the Solar Heat Load in a fictive room based on one square meter of the exterior wall with the quotient of Area window over Area exterior wall to determine how much of the irradiance that gets into the building. With a distinguished room depth the Solar Heat Load can be found.

Mean U-value

By the areas of the different construction elements multiplied by their U-values a mean U-value can be calculated. Since this step is not for the analysis grid, just by adding the elements characteristics together, this calculation is performed automatically and not time consuming at all.

4. Results

The results achieved by running the simulations and calculations in the methodology are presented in different ways. The purpose of all these ways to present them is to be able to dig deeper into a certain indication. All the steps are explained below.

Data management

The data management in the methodology serves two purposes. The main purpose is to present the results from simulations in a suitable tree structure, this in order to sort the results to each object, see Figure 5. The secondary purpose is to set the limits of the domains related to the choice of grade in Miljöbyggnad.

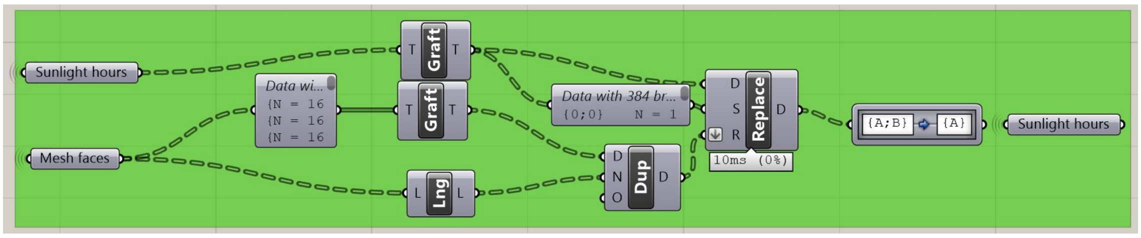


Figure 5 Data management in order to relate the results of a simulation to each building.

Plot of actual results

First of all the results are shown as actual numbers, they are not grouped. The results are still presented with a legend of the same colours indicating if they are of positive or negative kind.

Aggregation for each indicator

To be able to show the results grouped into the Yes, Maybe and No categories a sorting system is required. In Figure 6, the process of sorting results is shown. The results get replaced with a number corresponding to the different groups, 1 stands for Yes, 0.5 for Maybe and 0 for No.

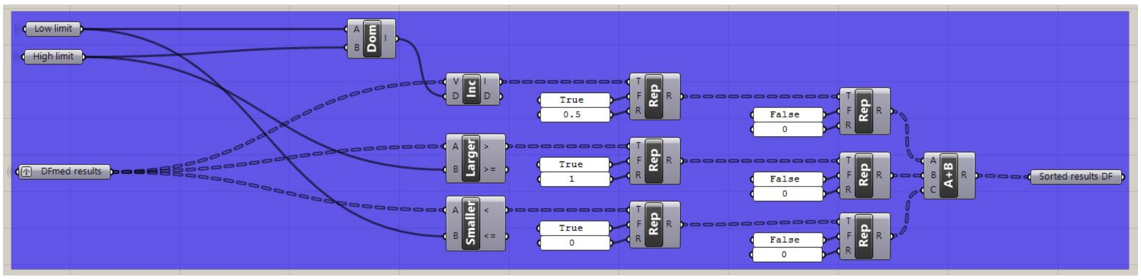


Figure 6 How the actual result are grouped into Yes, Maybe and No.

Plot for aggregated results

After gathering the results in groups of indicating answers they are mapped onto the analysed surfaces. There are just three colours where green indicates Yes results, yellow for the Maybe group and Red for the ones indicating No.

Total summation

As a final way of presenting the results the grouped results are first counted for each grid point per metric (see Figure 7). By distinguished domains a single and final result is presented on the analysed surface, the process can be seen in Figure 8 and the domains are presented in Table 1.

Table 1 The domains for deciding whether a grid point should be determined as a Yes, Maybe or No point.

	Yes	*Maybe*	*No*
Aggregated summation	3 Yes	≥ 1 Maybe + rest Yes	≥ 1 No

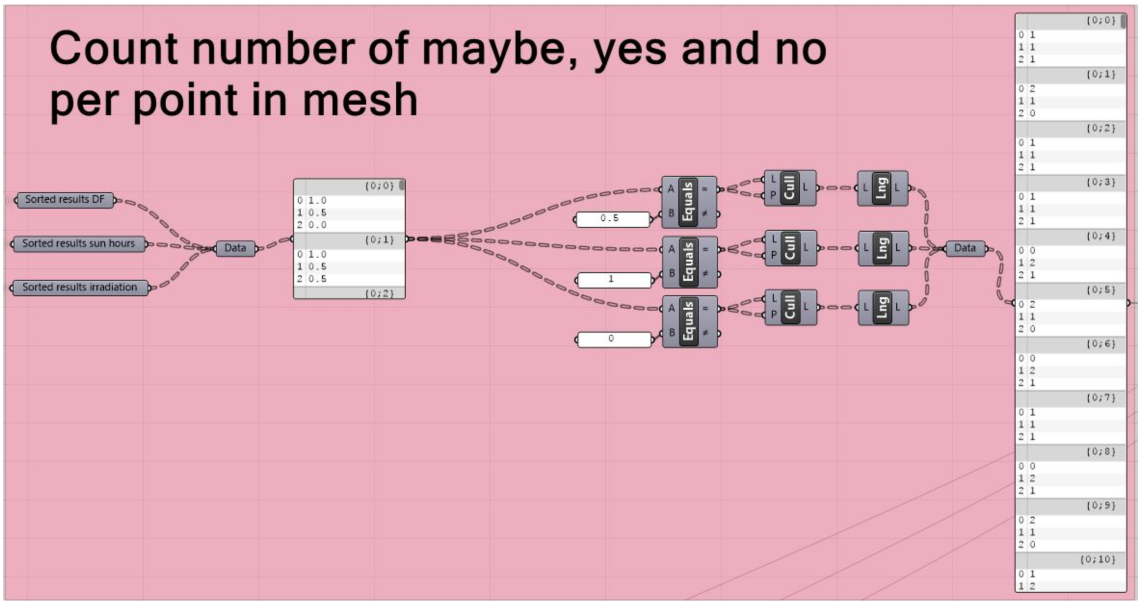


Figure 7 Counting the number of each group per metric and grid point.

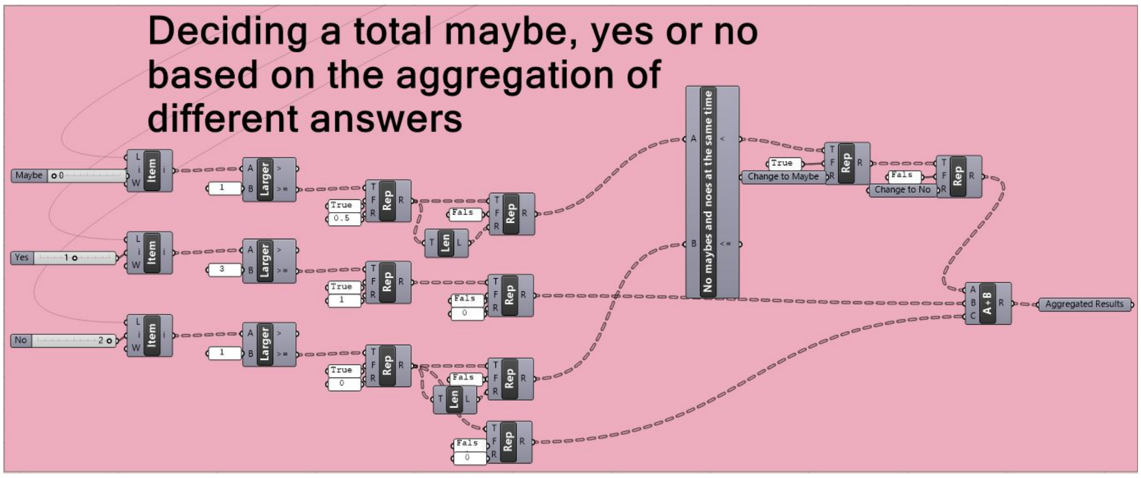


Figure 8 By the same manner as for aggregating the results for each metric each grid point is graded to Yes, Maybe or No depending on the number of a certain grade in the previous step.

Plot of total summation

The final colour mapping is performed in this last step. The mapping is performed in the same way as for the aggregated results but the difference here is that depending on the results from each metric the grades are counted and from the distinguished conditions a final answer for each grid point is provided.

Appendix E - Supplementary material from case study 1 - Lindholmshamnen

The following appendix includes additional inputs and results from the first case study. Table 1, presents the input data for the second and final iteration (the first simulation and first iteration have been presented in Section 5.1).

Table 1 The table shows the building parameters that have been adjusted in the second iteration and final iteration.

Building parameters	1	2	3	4	5	6
Number of floors	3	8	6	7	4	6
$A_{glass}/A_{room.floor}$ [-]	0.3	0.3	0.3	0.3	0.3	0.3
Room depth [m]	4.0	4.0	4.0	4.0	4.0	4.0
Shading factor [-]	0.7	0.7	0.7	0.7	0.7	0.7
g-value [-]	0.55	0.55	0.55	0.55	0.55	0.55
U_{window} [W/m^{2}K]	1.1	1.1	1.1	1.1	1.1	1.1
U_{wall} [W/m^{2}K]	0.16	0.16	0.16	0.16	0.16	0.16
$U_{foundation}$ [W/m^{2}K]	0.15	0.15	0.15	0.15	0.15	0.15
U_{roof} [W/m^{2}K]	0.13	0.13	0.13	0.13	0.13	0.13

Results

In the following figure, the results are presented for the first iteration of the case study. The total aggregated results for all four metrics were shown in Section 5.1.3. The results in Figure 1, are still aggregated into Yes, Maybe and No, but presented for each metric separately in order to understand how each metric was affected by the changes made in the design.

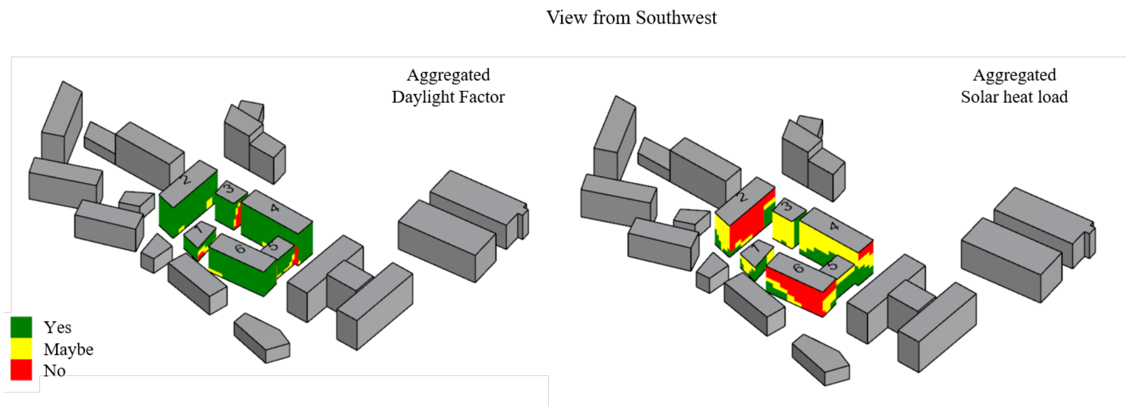


Figure 1 Aggregated result from the first iteration for the DF_{median} and Solar Heat Load in the south-east direction. The result indicates that the daylight criteria is fulfilled while the solar heat load is still problematic for some parts of the buildings.

The sunlight hours cannot be improved by any changes in the design of this case study, but still needs to be satisfied, which is therefore this metric is included in the evaluation. For this case study, one can see how the sunlight hours for this residential area performs in Figure 2.

Aggregated Sunlight hours

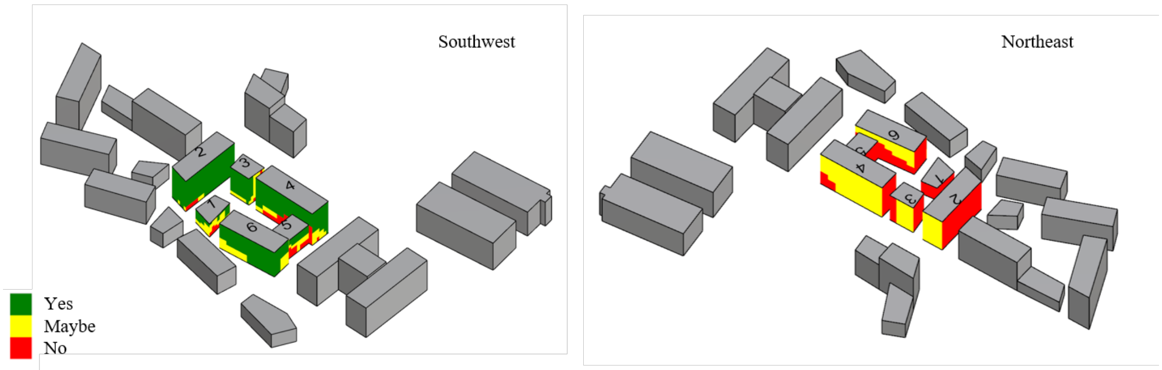


Figure 2 *Aggregated result for sunlight hours in both southwest and northeast direction. As the figure shows, the northeast façades unfortunately do not meet the requirement and need extra attention when designing the layout of the building.*

Appendix F – Supplementary results from case study 2 – Project X

This appendix contains extra material of the results from case study 2 (Section 5.2). Due to the confidentiality, additional input parameters or information about the case study cannot be presented.

Figure 1, shows a supplementary result from the DF simulation based on the developed methodology. For the colours from red to light blue, the DF does not meet the requirement. These areas would need improvement to the design. Since the purpose of this case study was to verify the distinguished correlation, the figure is added if the reader wants to further evaluate the distribution of the DF.

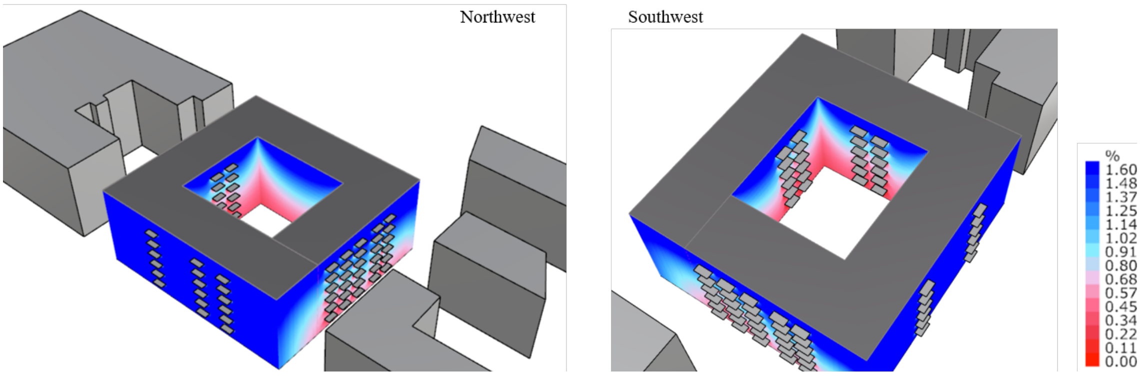


Figure 1 Supplementary simulation results for other cardinal directions.

Figure 2, presents the actual results for the DF, in pre-calculated result (dark blue) and simulated result from the developed methodology (light blue). As the figure shows, there are rooms where the value for the DF_{median} differs a lot (room number 1, 4, 5, 8 and 10) and there are rooms where smaller deviations occur. What should be noted is that room number 1, 4, 6, 7, 11 and 13 are rooms where balconies have not been added. For the rest of the rooms one could expect larger variations of the results. Even though, there are rooms which are considered to be on the "safe side" and rooms which are not, the actual differences between the values are in percentages, not percent, which is a small marginal.

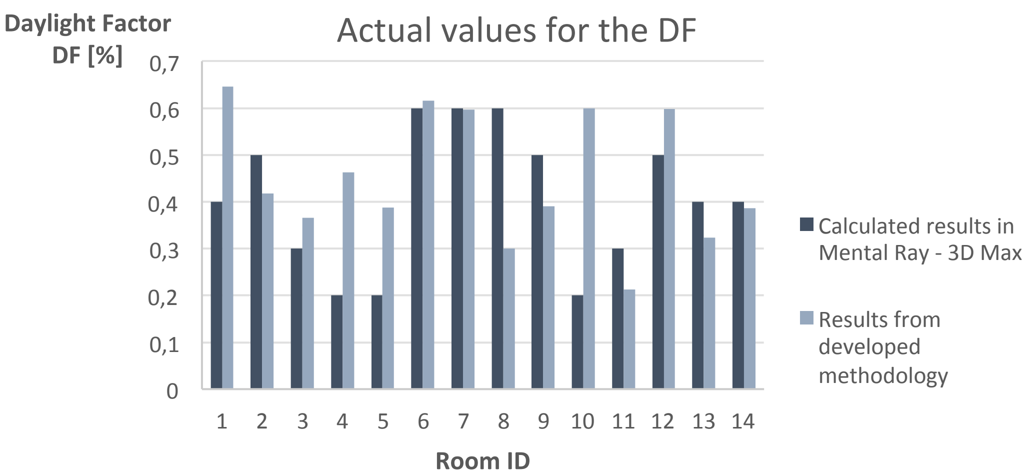


Figure 2 Actual results for the comparison of the DF_{median} between the pre-calculated values (in dark blue) and the simulated values (in light blue).