The effect of an atrium and building orientation on the daylighting and cooling load of an office building.

An early stage study

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The effect of an atrium and building orientation on the daylighting and cooling load of an office building

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Last but not the least, I thank White Arkitekter, one of Scandinavia’s largest architecture house for providing me the scholarship to work on a theme of great relevance to them, i.e., early stage collaboration between engineers and architects.
Abstract

The thesis is an outcome of a collaborative work between the author and an architect. It aims to answer design questions that were posed in the early stages by the team of a student architect and the author himself relating to the daylighting performance of the building located in Stockholm, Sweden. Two design elements of interest that were to be evaluated were decided: the orientation of the building and the effect of introducing an atrium in the building. Annual daylighting performance simulations were carried out and these two design elements were parametrically varied to see the effect on the daylight distribution inside the building for the given architectural model. For the same design parameters, an energy model was created and simulated to see the effect of these design alteration on the cooling loads of the building. The importance of early stage collaboration between engineers and designers have also been discussed which sets the contextual scene of the thesis.
Glossary

**Atrium**: An atrium (pl. atria) can be described as a covered courtyard (usually by glass), a courtyard being an internal void within or between buildings that is open to the sky. It helps in bringing daylight to the interior of deep plan buildings where daylight from the side cannot penetrate. [30]

**BPS**: Building performance simulation.

**Cooling load**: Cooling load is the rate at which sensible and latent heat must be removed from the space to maintain a constant space dry-bulb air temperature and humidity. [19]

**Daylight Autonomy**: The daylight autonomy at a point in a building is defined as the percentage of occupied hours per year, when the minimum illuminance level can be maintained by daylight alone. [26]

**Daylight Factor**: It is defined as the ratio of the indoor illuminance at a point of interest to the outdoor horizontal illuminance under the overcast sky. [26]

**Daylighting**: Daylighting is defined as the controlled admission of natural light; i.e. direct sunlight and diffuse skylight into a building to reduce electric lighting and save energy. [3]

**Illuminance**: The amount of light falling on a surface per unit area, measured in lux. [32]

**Irradiance**: It is the radiative power of the solar radiation on a physical or an imaginary surface. [19]

**Irradiation**: It is the radiative energy of the solar radiation during a certain time interval such as an hour or a day on a physical or an imaginary surface. [19]

**Luminance**: It is defined as the quantity of light energy emitted, reflected or transmitted from an object in a given direction. This object can be a physical object or an imaginary plane. It is the only form of light we see. It is measured in candela per square meter. [22]
Solar heat gain coefficient: The solar heat gain coefficient is the fraction of incident solar radiation admitted through a window, both directly transmitted and absorbed and subsequently released inward. SHGC is expressed as a number between 0 and 1. The lower a window’s solar heat gain coefficient, the less solar heat it transmits. [6]

U-value: U-value is the overall heat transfer coefficient that describes how well a building element conducts heat or the rate of transfer of heat (in watts) through one square metre of a structure divided by the difference in temperature across the structure. Expressed in W/m²K in SI units. [14]

Visible Transmittance: It is a measure of how much visible light is transmitted through a given glazing material. [3]
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<td>[%]</td>
</tr>
<tr>
<td>DF</td>
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<td>[lux]</td>
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<tr>
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Chapter 1: Introduction

1.1 Introduction

Form and function of a building are two sides of the same coin. Form or the structure determines how volumes of spaces are arranged together in order to provide for human activity to take place based on knowledge of social sciences and arts. Function controls how the structure interact with each other and the environment based on the thermodynamic interactions through different heat transfer processes and mass transfer across the system.

Architectural practice nowadays require their designers to look for sustainable solutions. This essentially involves being able to relate the building design elements to temperatures and loads that are associated with buildings. Therefore, it makes sense either for a designer to learn the fundamentals of building physics or the building scientist to learn the working of the designer when the search for environmental friendly design solutions is one of the goal. Another way is collaboration. The thesis aims to answer the latter question. A collaboration with a student architect resulted in questions being asked, “Does the orientation of the building affect the daylighting in the building?” and “Can I improve the daylighting by introducing an atrium and how much?”. As a building engineer I asked a question, “Are the building heating and cooling loads changing with change in building orientation?”. An experienced building designer can perhaps answer these questions right away but given the nature of the building industry, every project comes with its own set of constraints and before an answer is given, a thorough investigation is required.

The author aims to answer such questions that were posed in a collaborative early stage design process between the author and a student architect, hence paving the way for more environmentally conscious decision making.
1.2 Background

Requirements relating to the performance of the building in terms of occupant satisfaction and energy is becoming very demanding. These requirements are often driven by building regulations in place but also depends on goals and values of the project developers. The implications of these requirements translates into lower operational costs and reduced use of resources, driving a more sustainable development. A project goes through various stages from early design stage to the construction stage. The conceptual stage or the early design stage is the best time to integrate sustainable strategies as these mechanisms when implemented at the start of the project results in lower costs. [34] Traditionally, as the project progresses, the cost of design changes increases and the ability to impact design and functional capabilities decreases. [1]

A project begins with the architect conceptualizing the project based on the clients requirements and then begins the exploration of design space. Parameters such as shape of the building, orientation, glazing, etc. are decided upon during this stage. Along with thermophysical properties of the building material, these elements play a huge role in designing high performing buildings. [7] Questions relating design elements to the building performance are asked during this stage and a lack of understanding of the principles of building physics leaves the architect with two options: either to learn the fundamentals of building physics or collaboration with a building scientist to support design decisions. [31]

Supporting design decisions in early stage is a very popular topic in the research community which either discusses the importance of collaboration with the building scientist or is involved in making novel tools that help architects to understand the implications of their designs in a very simplified manner. [4], [16], [18] The former question has been attempted in the thesis wherein a project specific problem has been investigated to understand the working of an architect and support in understanding different design options.

The author collaborated with an architect and certain design ideas were studied. Key questions that were asked related to the orientation of an office building and how it affected: the daylighting performance and the peak loads of the building during its operation. Introducing daylight into a building can reduce dependency on artificial lighting and can lead to lower energy consumption. This is especially true for non-residential buildings, as was the case for the thesis, which depend a lot on artificial lighting. [30] Daylight can be introduced in the spaces on the perimeter of the building by using windows but for deeper buildings where light cannot penetrate from the sides, other strategies are used. To that end, it was decided to introduce an atrium into the building which would not only increase the daylight in the already day lit regions but also introduce light into the more deeper zones of the buildings. As a building scientist, the implications of these designs / design changes on the loads of the buildings was not just an interesting question to answer but also very relevant to the subject matter of the thesis.
The aim of the thesis is to support design decision in the conceptual stage by exploring the effects of building orientation and shape on the daylighting performance of the building and the associated peak loads of the building. This includes familiarizing with the working of the designer and learning different modes of exchange of relevant information.

1.2.1 Limitations

The work done and the results obtained is specific to the architectural model studied. The author began the study after certain design elements were already decided: number of floors, shape of the building, fenestration and the function of the building. The collaboration was time intensive due to a lack of information and time consuming modelling. This study can be used as a reference for similar studies but given the nature of the industry, every project comes with its own set of variables and deliverables, a thorough investigation and different approaches must be used.

1.2.2 Expected outcome

The purpose of the project work was to gain understanding of three key concepts/processes: daylighting, cooling loads and early stage design. The author has attempted this by collaborating with an architect and answer questions that were posed during an early design stage. These questions related to daylighting performance and the peak loads associated with the building during its operation by doing a parametric study on the building orientation and the atrium. The whole process was complimented by author’s own background in building services which provided a holistic view to approach the questions that were asked.

The author would have learned how to:

- Remedy collaborative issues that arise due to missing or extra definitions in architectural building models that are needed before running detailed simulations.
- Model in Rhinoceros 3D\(^1\) and use the models to perform daylighting analysis in Honeybee\(^2\) for Grasshopper.
- Set up detailed energy models in a building performance simulation (BPS) tool called IDA ICE\(^3\).

---

\(^1\)See section 2.5.1  
\(^2\)See section 2.5.1  
\(^3\)See section 2.4.1
1.3 Literature study

Evaluating the impact of solar radiations on a building has twofold benefits. With reference to a building geometry, it can give us an idea of the daylighting potential and the impact on the building loads. To keep a building space at desired conditions of human occupancy, the heat that must be supplied or removed is called the load. The heat gains due to the solar radiation is one of the factor that controls the total cooling load or the heating load of a building. The contribution of the solar radiations is most important for the cooling loads since the peak happens during summer at noon time when it is very sunny. Heating loads usually peak during cold winter nights when the sky is clear and there is no sun. [19]

Shape of a building can give us an idea of how much of the surface is exposed to the outside, hence to heat exchange between the environment. Thus, a very compact building would have very low outer surface to volume ratio with lower heat exchange as compared to shapes with the same volume. This affects the surface area that is exposed to the sun as well. Similarly, depending on the latitude, the orientation of the building also changes the amount of radiations it receives. Therefore, these two building design parameters are usually studied together. [2], [7], [15], [24] To demonstrate the combined effect of the two parameters, [2] could reduce the heating consumption by 36 % of a building located in a cold region of Turkey by playing with the shape factor and orientation. [8] could achieve a decrease in cooling requirements of an apartment located in Amman, Jordan by 25 % just by shading the whole building throughout the cooling season.

Most of the research work has focused on conventional parallelepiped building shapes and how all the façades face the cardinal directions. [12], [21] concluded that a rectangular house would perform better in heating and cooling if the longest wall faced South. [2] in their study on orientation and heating demand also found out that their rectangular building with its longest wall facing South performed better.

Both shape and orientation not only provide opportunities for manipulating the solar gains that influence the cooling loads and energy demands of a building but it can also play a crucial role in how the daylight enters the building. For instance, glazings play a crucial role in bringing natural light into the building but it can also lead to unnecessary solar heat gains. This not only depends on the solar heat gain coefficient (SHGC) of the glazing but also how it is oriented. In general, increase in glazing leads to increase in solar penetration both in terms of daylight and heat.

Modern tools that assist in evaluating building performance can help a building

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4 The shape factor is the ratio of building length to building depth.
5 The SHGC is the fraction of incident solar radiation admitted through a window, both directly transmitted and absorbed and subsequently released inward. SHGC is expressed as a number between 0 and 1. The lower a window’s solar heat gain coefficient, the less solar heat it transmits. (31)
simulationist to place the building in the context and arrive at informed decisions where the trade-off between two aforementioned building requirements (i.e., daylighting and the cooling loads) is not apparent. Therefore, evaluating the impact of orientation of a building on the solar heat gains (Both through the opaque surfaces of the building and solar heat gains through the glazing) and the daylighting potential of a building can lead to useful insights when the design is in an early stage. Even though daylighting can replace artificial lighting and provide for lower energy bills [30], it could also adversely affect the cooling load of a building in some cases when proper solar control strategies are not in place. [17]

[28] in their paper titled, ‘Irradiation modelling made simple: the cumulative sky approach and its application’ present to us a novel technique in which annual irradiation results can be obtained over a building with help of a backward ray tracing simulation tool called Radiance in a single run. This approach is very useful since it can be used to calculate the solar exposure over the building geometry throughout the year but can also be useful in predicting daylight levels either inside based on the latitude and weather conditions of the place with relatively low computational time.

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6See section 2.5.1
Chapter 2: Methodology

2.1 Work flow

The whole process from the beginning of the project until the results were obtained can be divided into 6 important stages: concept stage, model exchange, modelling, simulation and results collection and representation. Figure 2.1 depicts the flow in which these stages were followed.

Figure 2.1: Work flow.

2.2 The concept stage

At this stage, the collaborating architect began to work on designs that were to form the basis of the model that would later be used for detailed daylighting, energy, and indoor environmental modelling to aid the architect during the design stage. A building was to be designed that would be in the new developing Albanova campus site under development which lies between KTH Royal Institute of Technology and Stockholm University in Stockholm, Sweden. The designer in her own capacity as an artist and an advanced modelling tool user worked on a lot of designs to generate models in Revit\(^1\).

This building was conceptualized by the architect to have both residential and non-residential spaces that would cater to post doctorate students as accommodation and office spaces. However, in order to narrow down the analysis the function of the building was fixed only to provide for non-residential spaces.

A model as shown in Figure 2.2 becomes the starting point of the analysis. This architectural model is one of the many models that were created by the architect.

\(^1\)Autodesk Revit is a building information modeling software for architects, structural engineers, MEP engineers, designers and contractors developed by Autodesk.
and captures the shape of the building, space distribution, glazing distribution, orientation of the building and location.

2.3 The model exchange

The model was created in Revit 2014 and shared as an ‘.rvt’ file. The file then was converted to Revit 2015 file and then analyzed. To use the model in IDA ICE, it had to be converted to an IFC\textsuperscript{2} file format. To that end, the ‘export to IFC’ function was used in Revit 2015. This IFC file which when imported to IDA ICE using the import function had certain shortcomings.

\textsuperscript{2}It is a platform neutral open file format specification which stands for Industry Foundation Classes and is intended to describe building and construction industry data. It is widely used in the architecture and engineering domain for collaboration.
The spaces on all the stories were missing as can be seen in Figure 2.3b, in contrast to the spaces in the floor plan in Revit as seen in Figure 2.3a. This is essential in order to create thermal zones\(^3\) that corresponds to the spaces correctly in the original model.

Using the visual filter function in IDA ICE, it was found that the IFC file did have the building body intact and some IFC definitions (Fig. 2.4) but not the definitions that were essential for performing building load simulations.

![IFC definitions.](image1) ![The building body.](image2)

**Figure 2.4:** Architectural model as seen in IDA 3D view.

The software could not recognize the spaces that were contained in the original Revit file hence certain modifications had to be done for it to work. In Revit 2015, the space definitions were fixed for each floor. Final fixes were done in Simplebim\(^4\) in which a lot of extra information that was not required were removed to make IFC light and usable for IDA ICE.

The final IFC now had spaces which could be selected and easily converted to zones in IDA ICE. Properties associated with the spaces were also now understood and fixed, as shown in Figure 2.5. The location, name and size of the zones were fixed now along with the orientation of the building.

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\(^3\)Thermal zones are spaces that are conditioned by heating, cooling and ventilation systems. EN ISO 13790:2008 provides the criteria to define thermal zones.

\(^4\)Simplebim is a software used to fix and validate IFC models. Irrelevant objects and properties can be removed or new ones added to prepare the IFC file for the use in IDA ICE.
2.4 The energy model

2.4.1 Tools

The author used IDA Indoor climate and Energy (IDA ICE) to perform the cooling load calculations. It is developed by EQUA Simulations AB, which is a whole year building performance simulation (BPS) tool providing capabilities to carry out energy, thermal, indoor air quality and most recently daylight calculations. [9] 

Building geometry and floor plans from CAD files can be imported to the program using the IFC file format. A comparison done by [35] of various building simulation tools, with an emphasis on early stage design, IDA ICE could be used during the preliminary and detailed design stages of the building process.

2.4.2 Standard model

An energy model to evaluate the cooling loads associated with the building was created in IDA ICE 4.7. Definitions pertaining to an office building to provide for an acceptable indoor environment were fixed. These decisions were based on relevant standards and default options available in the simulation tool and are mentioned in the subsequent sections wherever they are used. For instance all the physical structures like walls, floors etc. were chosen from the default constructions provided by the tool.

Geometry of the building

The building shown in Figure 2.6 would serve to provide for office spaces located in Stockholm, Sweden. The gross floor area of the building was 3885 m² and the office
spaces made up 16320 m\(^2\). The building had 8 stories and a room height of 2.7 m for all the floors and 3 m for the top floor. The distance between the floors was 3 m. The building has a peculiar shape with no prominent façade and includes an enclosed atrium well.

![Building model as seen in IDA ICE.](image)

Figure 2.6: The building model as seen in IDA ICE.

**The layout of the floors**

The building serves to provide for open plan type office spaces which is quite common in Sweden. The layout of zones in general for each floor is common, even though their intended function can be different. Two different floor types were identified: external floors (floor 0 and 7) and internal floors (floor 1-6). Figure 2.7 shows the floor layouts as seen in IDA ICE.

Since the floor plan including the intended function was common for the internal floors 1-6, so as to reduce the simulation time, all the zones on floor 1 acting as a template was multiplied by 6 (Fig. C.1 and C.2). This is a valid and reasonable strategy to reduce the simulation time since it was assumed there were no adjacent buildings shading the building and all the internal building elements (floors, ceiling and walls) were considered adiabatic (no heat exchange). The external floors, floor 0 and 7, were simulated separately since the boundary conditions were different. The former was in contact with the ground and the latter was in contact with the atmosphere. Table 2.1 lists the zone types, their associated numbering on different floor levels with the multiplication factor used.

**Occupancy**

There are two types of office spaces in the building: Open plan office type and meeting rooms. It was assumed that area per occupant would be 14 m\(^2\) for the open plan arrangement. For the meeting rooms it was assumed that area per occupant
2.4. THE ENERGY MODEL

Figure 2.7: Distribution of zones for the two floor types.

<table>
<thead>
<tr>
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<th>Zones</th>
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<tr>
<td></td>
<td>Floor 0 (x1)</td>
<td>Floor 1 (x6)</td>
<td>Floor 7 (x1)</td>
</tr>
<tr>
<td>Open plan office</td>
<td>1,2,3,4,11</td>
<td>1,2,3,4,10</td>
<td>1,2,3,4,11</td>
</tr>
<tr>
<td>Meeting room</td>
<td>6,7</td>
<td>5,9</td>
<td>6,7</td>
</tr>
<tr>
<td>Kitchen</td>
<td>9,10</td>
<td>6,8</td>
<td>9,10</td>
</tr>
<tr>
<td>Bathroom</td>
<td>13,15</td>
<td>12,14</td>
<td>13,15</td>
</tr>
<tr>
<td>Corridor</td>
<td>8,12,14,16</td>
<td>7,11,13,15</td>
<td>8,12,14,16</td>
</tr>
<tr>
<td>Atrium</td>
<td>5</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Staircase</td>
<td>17,18,19,20</td>
<td>17,18,19,20</td>
<td>17,18,19,20</td>
</tr>
</tbody>
</table>

Table 2.1: Zone types on different floor levels and their associated multiplicity.

would be 6 m². Open space type has an area of 16320 m² with a capacity of 1165 occupants. The bottom and the top floor have 1 meeting room each with a capacity of 18 occupants while the rest of the floors contain two meeting rooms each with a capacity of 9 occupants. For the open space type it was assumed that only 80% of occupants would show up. For the meeting rooms it was assumed that they shall only be used 50% of the time and shall be used only 80% to their capacity. Table 2.2 summarizes the occupant densities and the schedules associated with each zone type.

The corridor, kitchen, staircase and the bathroom were assumed to have no occupancy. In the atrium well, one occupant was included as it would be required by the software to calculate the PPD\textsuperscript{5} values. It was also assumed the occupancy is zero on weekends and holidays and reduced to 50% during the month of June, July and August.

\textsuperscript{5}Percentage of people dissatisfied: A method to define comfort based on heat-balance equations and empirical studies based on skin temperature, developed by P.O. Fanger.
2.4. THE ENERGY MODEL

<table>
<thead>
<tr>
<th>Zone Type</th>
<th>Occ. Density (occupants/m²)</th>
<th>Schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open space type</td>
<td>0.0714</td>
<td>8-12, 13-17</td>
</tr>
<tr>
<td>Meeting room</td>
<td>0.16</td>
<td>10-12, 13-15</td>
</tr>
<tr>
<td>Kitchen</td>
<td>0</td>
<td>8-12, 13-17</td>
</tr>
<tr>
<td>Bathroom</td>
<td>0</td>
<td>8-12, 13-17</td>
</tr>
<tr>
<td>Corridor</td>
<td>0</td>
<td>8-12, 13-17</td>
</tr>
<tr>
<td>Atrium</td>
<td>1 occupant/zone</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.2: Occupant density and schedule.

**Lighting and equipment**

The installed lighting power density was assumed to be 13 W/m² for the open plan office space and meeting rooms for the desired illuminance of 500 lux at the desk. This value corresponds to an average lighting power density of an inventory of 123 Swedish office buildings of varying age by the Swedish Energy Agency. [33] The luminous efficacy\(^6\) of the lights were set to 38.46 lm/W. For the kitchen, a value of 5 W/m² was used. The bathroom, corridor, kitchen and the atrium space were assumed to have no installed lighting.

A computer of 150 W per occupant was considered for the open office space type. An all in one printer of 500 W was considered per 20 occupants which makes it 175 W per occupant in total for the open office space type. This makes it 12.5 W/m² for the open space type. For the meeting rooms and the atrium it was assumed that 2 computers were present during working hours. The kitchen and the bathroom have 7.5 and 0 W/m² respectively.

**Heating, ventilation and cooling**

To take care of the heating and cooling requirements of the building, ideal heaters and ideal coolers were used. These are room units that can be put in the zones when information regarding only heating and cooling loads is required, which was the case in the present study. The ideal heaters and coolers used in the building were PI (Proportional-Integral) controlled.

For the open plan office type, a CAV (constant air volume) of 8.5 l/s per occupant was provided while for the meeting rooms a VAV (variable air volume) controlled by the amount of CO\(_2\) in the zones was used. The bathroom and the kitchen have only return air of 2 and 1 l/s.m\(^2\) respectively. For the atrium space, only re-circulation at the rate of 1 l/s.m\(^2\) was provided with no supply air. Two AHUs (air handling unit) were used: one serving the atrium and the other serving the rest of the zones. It is a common strategy to have a standalone air handling unit for the atrium spaces.

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\(^6\)Luminous efficacy is a measure of how well a light source produces visible light. It is the ratio of luminous flux to power, measured in lumens per watt in SI units.
Control set points

All the heating and cooling units in the zones were set to keep the temperature between 21°C to 25°C. For the atrium it was set to keep the temperature between 19°C and 29°C. The atrium space was allowed more buffer as these spaces usually act as circulation places for people and higher lower temperatures do not add to discomfort to the occupants.

Thermal comfort

For the purpose of this building, an indoor environment quality that corresponds to category number three according to EN 15251 has been chosen (Category C according to EN ISO 7730). [10] For this category, 90% of the working hours with Predicted Percentage of Dissatisfied (PPD) occupants less than 15% was chosen to be the limit that the building would aim to provide.

<table>
<thead>
<tr>
<th>Category</th>
<th>Thermal state of the body as a whole</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PPD</td>
</tr>
<tr>
<td>III</td>
<td>&lt;15%</td>
</tr>
</tbody>
</table>

Table 2.3: The indoor environmental quality benchmark. [10]

Building element

Table 2.4 represents the thermal transmittance of the different building elements that have been used in the building.

<table>
<thead>
<tr>
<th>Building element</th>
<th>U-Value (W/m².K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External wall</td>
<td>0.2236</td>
</tr>
<tr>
<td>Internal wall</td>
<td>0.6187</td>
</tr>
<tr>
<td>Roof</td>
<td>0.172</td>
</tr>
<tr>
<td>Ground Floor</td>
<td>0.3305</td>
</tr>
<tr>
<td>Internal floor</td>
<td>2.385</td>
</tr>
</tbody>
</table>

Table 2.4: Thermal transmittance of the building elements.

Glazing

Only one type of glazing was used for the whole building with U-value as 1.1 W/m².K, visible transmittance (Tvis) as 0.71, solar heat gain coefficient (g) as 0.43. This particular glazing has properties which allows for higher light transmittance and allows for lower solar gains that leads to higher cooling loads. [23]
2.4.3 Assumptions

- There were no external obstructions around the building.
- Weather file for Stockholm was chosen.
- Change in orientation of a building changes not only how the solar radiations hit the buildings but also the wind pressure around the building which affects the leakage in the building. In order to eliminate the affect of wind pressure, fixed infiltration values of 0.5 ACH was chosen.
2.5 The daylight model

2.5.1 Tools

A good part of the time was spent in familiarizing with these tools and exploring the functions that were necessary to carry out the daylighting calculations. These tools can be used during preliminary and detailed design stages and provide for parametric analysis of different design options. [35]

Rhinoceros

Rhinoceros is 3-D modeller used to create complex geometries. It can be used to make, edit and analyze curves, surfaces, solid objects. All Rhino geometry is represented in the NURBS\(^7\) mathematical model which helps it in accurately representing a 3D geometry. Rhino finds its application in various fields like architecture, industrial design, product design etc. [27] The software was used to create an exact model of the building representing the building geometry. In order to use the building definition for the purpose of parametric analysis and re-modelling, the software was coupled with a generative algorithm extension called Grasshopper.

Grasshopper for Rhino

Grasshopper is a free generative algorithm extension that is used in conjunction with Rhinoceros to generate, edit and analyze geometries based on a user defined algorithm. [13] It can be used to perform parametric analysis wherein a user defined rule set defines and creates 3D objects or architectural elements. This extension provides various form and logic creating components which when connected together to create an algorithm can manipulate design elements in a project. These components or mini programs can be created by dragging them on to the Grasshopper canvas. A change in the algorithm thus is executed and reflected in the design element which can be seen in the Rhino (short for Rhinoceros) scene. For instance, the glazing-to-wall ratio of a building geometry can be altered by using a numeric slider or a user defined logic when the geometric definitions of the glazing are linked to grasshopper, as seen in Figure 2.8.

Honeybee for Grasshopper

Honeybee is an open source environmental plugin for Grasshopper created by Mostapha S. Roudsari to help designers and engineers create environmental conscious design. [29] It can be connected to various building simulation software like EnergyPlus, Radiance, Daysim and OpenStudio to perform energy and daylight simulations. Using the parametric capabilities of Grasshopper, user defined material properties and design elements can be parametrically changed and their affect can be studied on

\(^7\)NURBS, Non-Uniform Rational B-Splines, are mathematical representations of 3-D geometry that can accurately describe any shape from a simple 2-D line, circle, arc, or curve to the most complex 3-D organic free-form surface or solid.
Figure 2.8: A set of grasshopper modules connected together to control the GWR of a building geometry.

Various performance indicators like daylight levels, indoor environment quality, energy consumption, cooling loads etc. These results, just like Grasshopper, can be seen in the Rhino Scene. It can be used for conceptual, preliminary and detailed designs. For this project work, Honeybee was used to perform daylighting study of the model. For this purpose, Honeybee uses both Radiance and Daysim which shall be discussed in the upcoming section.

**Radiance**

Radiance is a validated rendering package used to simulate illuminance and luminance distributions due to the sunlight for complex building geometries for different surface material properties for one sky at a time. It was developed by Greg Ward at Lawrence Berkeley National Laboratory. It uses the backward ray tracing technique wherein a point on the surface sends a ray in search of the light. [26]

**Daysim**

Daysim is a software, developed under the guidance of Christoph Reinhart at Harvard University, that utilizes the Radiance algorithms to calculate indoor illuminance and luminance profiles based on a weather file. These profiles can be used to predict daylight performance indicators like daylight autonomy, annual light exposure etc. [26]

### 2.5.2 Standard model

What constitutes a well daylit space is a question which is context specific and very subjective. However, to judge the daylight performance of a building, there exists different performance metrics which are used by building professionals. The two most widely used ones are *daylight factor* (DF) and *daylight autonomy* (DA). Both of these metrics are used by environmental certification system like Miljöbyggnad, LEED and BREEAM which provides various criteria that the building should fulfill to attain daylighting credits. Even though these metrics exist, there still lacks a
recognized performance metric to judge the ‘lighting quality of a space’. [26] Nevertheless, these metrics are widely used to judge the daylighting performance in buildings and the designer is free to choose these metrics depending on the project requirement and the goal. So in order to understand them, some definitions are in order.

**Luminance:** It is defined as the quantity of light energy emitted, reflected or transmitted from an object in a given direction. This object can be a physical object or an imaginary plane. It is the only form of light we see. It is measured in candela per square meter. [22]

**Illuminance:** The amount of light falling on a surface per unit area, measured in lux. [32]

**Daylight Factor:** It is defined as the ratio of the indoor illuminance at a point of interest to the outdoor horizontal illuminance under the overcast CIE$^8$ sky.

**Daylight Autonomy:** The daylight autonomy at a point in a building is defined as the percentage of occupied hours per year, when the minimum illuminance level can be maintained by daylight alone.

**Components of daylight**

The daylight that falls on a building has two components: direct daylight and diffuse daylight. Direct daylight originates directly from the sun while the diffuse daylight is the light that passes through the earth’s atmosphere. In addition, the building also receives light reflected off from surrounding objects. This light which a building receives depends on the luminous distribution of the hemisphere$^9$, which in turn depends on the condition of the sky. As soon as a weather file is imported in Daysim, a sky model is created that describes the luminous distribution based on date, time, geographical location, and solar radiations data imported from the weather file.

**Sky models and type of simulations**

**CIE Sky models:** These are sky types developed by the international commission on illumination (CIE) based on the relative luminous distribution of the sky, which in turn depends on the position of the sun and the parameters describing the atmospheric condition. [5]

**Perez Sky model:** Also called Perez all weather sky luminance model, takes input from the weather file and hourly irradiance values and calculates the sky luminous

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$^8$Commission Internationale de l’Éclairage

$^9$This physical quantity is usually represented by a two dimensional function which yields luminance values in different sky directions. [26]
distributions for the sky condition for a given analysis period. [25]

To know which kind of sky model that is to be used one needs to decide which kind of daylight simulation is to be performed, i.e., static or dynamic. Both of these simulations are used to calculate illuminance values at points of interest inside a building. For static simulations, a single standard CIE sky model is used. For instance, for daylight factor calculation, a CIE overcast sky\textsuperscript{10} model is used to calculate the illuminance on a sensor point inside a building for a single point in time. As this sky is 100% cloudy, the sky model has a uniform luminous distribution in all directions which makes this method rotationally invariant as can be seen in Figure 2.9a. Also, daylight factor calculations are only done for a particular time of the year. Daylight autonomy on the other hand, considers real sky conditions imported from the weather file which changes the daylight performance of the building with a change in orientation. This metric uses a sky model called Perez sky model which models all sky conditions for an analysis period and location as can be seen in Figure 2.9b. We can see that the luminous distribution of this sky is representative of a real sky which considers a real cloud cover and irradiation values imported from a weather file (Stockholm in this case). A Perez sky becomes a CIE overcast sky if the sky is very dark (cloudy). Therefore, DA as a daylight performance metric was used in the thesis as as the orientation of the building was one of the important parameter that was changed.

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{overcast_sky.png} \quad \includegraphics[width=0.4\textwidth]{perez_sky.png}
\caption{Condition of the sky in Stockholm on 21st June at 10 AM.}
\end{figure}

Inside the building the surfaces either receives this daylight from the sunlight transmitted directly from the fenestration, or it is received as light reflected off from other surfaces inside or outside of the building, or both. To calculate the amount of light present in a space or a point of interest, Illuminance values are calculated by the simulation tool.

\textsuperscript{10}CIE overcast sky is a sky with 100% cloud cover. This kind of sky is characterized by lower luminance and lower radiations and give out only diffused radiations.
2.5. THE DAYLIGHT MODEL

Illuminance values

Standard EN-12464 provides the recommended illuminance values based on the type of zones and the activity that takes place. It recommends illuminance value of 500 lux for activities which involve general office tasks which was the case in the thesis. [20] The sensor points at which the illuminance values were calculated coincided with the work-plane at a height of 0.8 m which also represents the typical height of an office desk. The occupied hours were chosen from 8:00 to 17:00 hours and the daylight autonomy simulation values were calculated for the whole year.

Reflectance values

For the reflectance values of the surfaces, the standard EN 12464-1 was refereed to and the recommended maximum values were chosen: For the Walls as 0.8, floors as 0.5 and ceilings as 0.9. [20] The ground reflectance was set as 0.2. [19] The specularity and roughness values were set as 0 for all the opaque surfaces.

Architectural features

A model representing the architectural features needed for daylighting study was recreated in Rhinoceros. This includes the building shape, orientation, division of floors and the glazing. In order to have more control over the design elements of the buildings, all the floors and the glazing were assigned different layers. For instance, if the day lighting analysis for only one floor was required in reference to the whole building, it could be done easily by removing the objects containing the definitions of the rest of the building. A flat ground geometry of 200m x 200m was also included in order to take into account the diffused reflections originating from the ground.

![Figure 2.10: The Model as seen in Rhino scene.](image)

The fenestration used represent the ones that were included in the architectural model and were not played with. The transmittance values for all the glazing were set to 0.71 in order to maximize the light passing through it. The architectural model was originally oriented 15° to the North. For better understanding of the
orientation, refer to Figure 3.1a.

2.5.3 Assumptions

- Weather file for Stockholm was used
- No buildings and shading objects were around the building.
- There were no internal obstructions like furniture, people, walls etc.

2.6 Data collection and representation

The effect of the orientation of the building and the introduction of an atrium were the two parameters that were being evaluated. In order to select the orientations at which the simulations were to be carried out, a preliminary analysis was performed to choose the orientations of interest\textsuperscript{11}. To take into account the change in the daylighting performance and the cooling loads due to an atrium, two models were created. For simplicity and quick understanding of the model being talked about, the model without atrium was labeled as ‘B’, akin to ‘base’. The model with atrium as ‘A’, akin to ‘atrium’. These labels would be used to refer both the types in the subsequent sections. These models were rotated anticlockwise about the axis passing through the centroid as can be seen in Figure 2.11a. To understand the relation between the angle of rotation and the direction the building pointed to, a compass rose figure was used, as seen in Figure 2.11. Figure 2.11 shows the base orientation of the building which points in the South-southwest (SSW) direction. This was the original orientation used by the architect.

\[\text{(a) Rotation direction.} \quad \text{(b) Compass rose.}\]

Figure 2.11: Base orientation and direction of rotation of the model.

\textsuperscript{11}\textnormal{See section 3.1}
Model B received light only through the facade glazing and model A received light from both facade and the interior glazing in the atrium well. A flat fully glazed atrium roof was chosen with 10% of the roof surface used by the frame. A flat roof chosen over others as the daylight autonomy in the adjacent spaces is not significantly affected with the change in the shape of the glazed roof. [11]

A grid of upward facing sensor points were created for each floor at which the daylight autonomy results were obtained as can be seen in Figure 2.12. The grid-size was chosen as 1m x 1m and these points were located 0.8 m above each floor level. Each grid point represented an area of 1 sq.m approximately. For each floor there were 3209 grid points at which the results were obtained.

![Figure 2.12: Sensor points at which daylight autonomy values are calculated.](image)

To understand and analyze the daylight autonomy results on each sensor point, different algorithms were generated using Grasshopper and Honeybee components to answer relevant questions. A color-mesh was created to visualize the daylight autonomy results for each floor (Fig. 2.13a). To find out the sensor points which would have zero daylight autonomy, the results obtained were used to represent these points with green dots for every floor (Fig. 2.13). The orientation of both the models B and A were altered in order to study the effect on the daylight autonomy values and the peak cooling loads of the buildings.

The cooling loads that were reported corresponded to the peak cooling loads of the whole building. Graphs used were obtained by the in-built plotting function in IDA ICE and their snapshots were taken.
Figure 2.13: Representation of the results on the base orientation.

(a) Color-mesh of daylight autonomy results.

(b) % of sensor points with zero daylight autonomy.
Chapter 3: Results

The section contains an analysis of all the results that were obtained after simulating the building for daylighting and cooling loads. These results have been complimented with an explanation and some relevant observations. All the Results from the irradiation analysis are collected in Appendix A, daylight autonomy results are collected in Appendix B and for the cooling loads in Appendix C. Whenever necessary, the author has referenced to the figures in appendices therefore the reader is requested to take a look at it whenever necessary.
3.1 Irradiation analysis: choosing the orientation

The irradiation analysis became the starting point for all the subsequent orientations that were to be evaluated for the change in the peak cooling loads and the daylight autonomy associated with the building. To take into account the solar radiations that would be received by the building surfaces, two building geometries were created. The first one would represent the model without the atrium well and second with an atrium well, as can be seen in Figure A.1c and A.1d respectively. Both the models were rotated anti-clockwise about their centroid in 10° and 15° steps for a full circle. The total solar energy received by the building body over the whole year was calculated, as shown in Figures A.2 and A.3 respectively. The model without the atrium well received maximum and minimum solar radiations when it was rotated 60° (Fig. 3.1c) and 195° (Fig.3.1f) from the base orientation. The model with the atrium well received maximum and minimum solar radiations when it was rotated 80° (Fig. 3.1d) and 195° (Fig.3.1f) from the base orientation. But it was observed later that the irradiation study for the model with the atrium well did not truly represent the distribution of solar radiations inside the atrium well because it depends on other properties like atrium roof glazing and the reflectance of atrium surfaces which obviously were missing in this initial study.

The literature review suggested that the longest façade should face the South or the North directions for better thermal performance and daylighting benefits and
since the building lacked any prominent facade, it was interesting to see how the
building would respond when it was aligned in the four cardinal directions (Fig.A.3
and 3.1e). Suggestions from the literature study and the results obtained from the
irradiation study led to only 6 orientations, as show in Figure 3.1, that were used
for daylight autonomy and the cooling load simulations.
3.2 Daylight Autonomy distribution

Two models were used to carry out this study. Building with daylight only from the glazing on the facade (i.e. model B as seen in Fig.B.1) and building with daylight from both the glazing on the facade and the atrium roof (i.e. model A as seen in Fig.B.2).

3.2.1 Building level

To understand the distribution and how far the useful daylight penetrates into the building, a script was created in Grasshopper to calculate the % of sensor points with daylight autonomy. This procedure could provide results floor wise and for the whole building. Two important observations were made: introducing an atrium and changing the orientation of the building changes the amount and the distribution of points with daylight autonomy inside the building. This can be seen in Figure 3.2. The blue bars correspond to the building receiving daylight from the glazing on the facade, model B. The red bars correspond to the building receiving daylight from both the glazing on the facade and the atrium roof, model A respectively (see appendix B for visualization of the models).

![Figure 3.2: % of sensor points with daylight autonomy: building level.](image)

In order to see the effect of daylight entering through glazing on the building facade, daylight autonomy simulation was performed for model B at the base orientation (Fig.3.3a). It was found out that 57.6 % of the sensor points were daylight autonomous, representing an area of 14787 sq.m. Now, an atrium was introduced in the building to increase the daylight entering the building which was confirmed by the daylight autonomy results (Fig.3.3b). This led to an increase by 23.07 % of sensor points with daylight autonomy corresponding to an area of 3410 sq.m. The
interior spaces of the building where daylight could not reach from the side alone now received light from the atrium. Daylight autonomy of the points in spaces around the atrium walls which were already autonomous due to the daylight from the facade also increased.

Simulations were performed for both model B and A at 6 different orientations. It was found out that for model B the daylight autonomy distribution inside the building changed and the building oriented at 195° (Fig.3.4b) reported the highest number of points with daylight autonomy (and also the most uniform). At this orientation, model B had 70.8% of points with daylight autonomy, representing an area of 18175 sq.m, i.e., 22.92% increase in the number of sensor points corresponding to an area of 3390 sq.m. by just changing the orientation.

Even model A oriented at 195° anticlockwise form the base position, reported the
maximum of sensor points with daylight autonomy at the building level (Fig. 3.5b).
At this orientation, model A had 80.53% of points with daylight autonomy, i.e., a
13.72% increase in sensor points and corresponding to an area of 2495 sq.m by just
introducing an atrium and changing the orientation (Fig. 3.5a and Fig. 3.5b).

(a) Orientation: 0° (SSW).
(b) Orientation: 195° (N).

Figure 3.5: Daylight autonomy distribution of model A on floor 4.

The atrium shape changed how the daylight was distributed in the spaces. In gen-
eral, the zones around the atrium facing South had more daylight autonomy pen-
etration as more direct rays coming from the South would enter these spaces. Due
to this reason, the maximum number of sensor point with daylight autonomy were
reported at 195° as well, shown in Figure 3.6. It is thought that the reason for this
is that at this orientation there is a maximum of zones around the atrium which
have components towards the South (the normal to these surfaces) therefore getting
more direct sunlight.

The results show that light coming from sideways (from the facade glazing) was
orientation sensitive as changing the orientation of the building led to a significant
increase in the number of points with daylight autonomy and this useful light went
deeper into the spaces. This was not the case if the building only had daylighting
from the atrium and the orientation of the building was changed, as was shown in
Figure 3.6. It was also observed that the daylight entering from the facade glazing
into the narrower zones could not travel further as it encountered an obstructing
wall. But when the building was oriented at 195°, the wide semi-circular zones
received light from both the high sun and the low sun owing to the placement of
the glazing which allowed light from all the sun positions. Also, this light travelled
further into the zone as there were no partitions that would block incoming light.
Overall, the building reported a 39.8% increase in sensor points with daylight au-
tonomy when an atrium was introduced in it and was rotated by 195° corresponding
to an area of 5885 sq.m.

Building orientation at 195° for both the models reported the maximum number of
3.2. DAYLIGHT AUTONOMY DISTRIBUTION

This is in contrast with the irradiation study which resulted in the orientation at 195° receiving the minimum amount of solar radiations at the building level. This is due to the fact that irradiation analysis only took into account the amount of solar radiation falling on the exterior of the building and did not account for the light penetrating into the building.

In the case of the thesis, daylight autonomy represents the % of time a sensor point would receive illuminance greater than 500 lux, it was also interesting to know at which orientations the building would receive daylight for longer periods of time during the occupied hours. In order to find that all the daylight autonomy values were summed up at different orientations and it was found that the building without
3.2. DAYLIGHT AUTONOMY DISTRIBUTION

atrium, model B, at 15° (Fig. 3.8a) performed better. As the atrium was introduced into the building, model A, this orientation changed to 105° (Fig. 3.8b). Figure 3.7 shows the sum of daylight autonomy results for both the models at all orientations.

![Daylight autonomy distribution of model B and A on floor 4.](image)

(a) Orientation: 15° (S).  
(b) Orientation: 105° (E).

Figure 3.8: Daylight autonomy distribution of model B and A on floor 4.

3.2.2 Floor level

It was observed that for model B, % of points with daylight autonomy did not change significantly with each floor, except for the bottom and the top floor. The values for the bottom and the top floors were consistently lower and higher respectively (Fig. 3.9a and 3.9c). It was thought the reason could be an increased number of reflected rays of light from the surrounding ground reaching the top most floor. As the atrium was introduced, model A, it was observed that the % of points with daylight autonomy increased consistently with each floor level (Fig. 3.9d, 3.9e and 3.9f respectively). The reason is that the view to the sky decrease with each decreasing floor and the amount of direct light that reaches them decreases. The lower most floor receives the least amount of direct light and is mostly lit by diffused light reflected from the interior walls of the atrium well. % of sensor points with daylight autonomy was also compared for model A for three floors: 0 (blue), 4 (red) and 7 (yellow), as shown in Figure 3.10.
3.3 Cooling loads

To see the effect on the cooling loads by introducing an atrium in the building two models were created. Model B had no atrium roof glazing while Model A had it...
(Fig. C.1 and C.2 respectively).

Cooling load simulations were performed for both model B and A at the building level for the same 6 different orientations. As expected model A had higher peak cooling loads due to the heat gains through the atrium glazing. What was interesting to note is that when the orientations were altered, the cooling loads changed and this change corresponded to the results obtained in the irradiation analysis that was performed earlier. The peak cooling loads for both the models at 6 different orientations can be seen in Figure 3.11. Orientation that received the maximum solar radiations in the irradiation analysis also had the highest peak cooling load, as shown in Figure 3.11. The total solar radiations received by the building and the peak cooling loads in increasing order is at these orientations:

$$60^\circ \text{ (SSW)} > 80^\circ \text{ (S)} > 15^\circ \text{ (SE)} > 0^\circ \text{ (ESE)} > 105^\circ \text{ (E)} > 195^\circ \text{ (N)}$$

The maximum difference between the cooling loads for model B was 27.2 KW and for model A was 26.6 KW between the orientation at $60^\circ$ (SE) and $195^\circ$ (N). Introducing an atrium in the building led to increase in cooling loads due to increase in solar radiations entering the conditioned atrium zone, hence more cooling was supplied to get rid of the excessive heat. Not only the conditioned atrium zone was heated up but also the zones around the atrium walls. The PPD values in all the zones for model B at all the orientations remained below 9 but for model A the PPD values in the atrium zone reached as high as 99. The capacity of the cooling systems and the air handling units were kept constant for both the models to observe the change when the roof glazing was introduced in the atrium zone. Upon investigation it was found out that solar radiations entering through the atrium roof glazing not only increased the air temperature (Fig. C.4) but also heated up the atrium walls as high as $46^\circ$ C which led to the increase in the PPD values. The atrium walls in the lower regions recorded lower temperatures as the view of the sky decreased and it received less direct sunlight.

What is interesting to note is that it was the orientation of the building that determined the cooling load values and a designer could get an idea which orientation to choose in order to lower the solar heat gains, consequently the cooling loads.

It is to be noted that atria are popular architectural forms to provide for daylighting on the atria floor and adjoining spaces. They have the potential to be sustainable strategies by replacing artificial light. As shown in the simulation, higher heat gains through the atrium roof can lead to higher cooling demands and energy consumption as the cooling systems would have to work more to keep the indoor environment in the atrium zone within the acceptable limits of human occupation. Therefore, atria are usually made use of in tandem with passive strategies like natural ventilation which uses the phenomenon of stack ventilation$^1$.

$^1$Stack ventilation is one form of natural ventilation which uses temperature differences to move air. Hot air rises because it is lower pressure. For this reason, it is sometimes called buoyancy ventilation.
3.3. COOLING LOADS

(a) Cooling loads of model B vs Orientation.

(b) Cooling loads of model A vs Orientation.

Figure 3.11: Cooling loads at the building level for the orientations of interest
Chapter 4: Conclusion

As a starting point, the irradiation analysis performed provided the orientations of interest that would be used to perform daylight autonomy and cooling loads simulations. The orientations receiving the maximum solar radiations also recorded the maximum cooling loads associated with the building. This method can be used to determine orientations at which a certain shaped building would achieve maximum and minimum solar radiations, consequently the orientations at which the cooling load would peak. It was found out that the building oriented at 195° recorded the lowest cooling load for the whole building and for both the models. The cooling loads were adversely affected as an atrium was introduced in the building due to heat gains through the atrium glazing.

Daylight autonomy results at different building orientations changed and provided an idea which zones inside the building would receive the useful daylight and which would be without it. It was found that when the building was rotated by 195° anticlockwise, there were maximum of sensor points inside the building that had daylight autonomy for both the models: with atrium and without atrium. Introducing the atrium led to an increase in the daylight autonomous points and the zones deep inside of the building now received daylight, as was expected. It was also observed that that the daylight autonomy distribution at this orientation was the most uniform for both the models.

The building with atrium rotated by 105° anticlockwise had daylight autonomous points that would stay autonomous for a longer period of time throughout the year during occupancy hours. Comparing the daylight autonomy results for 105° and 195° we see that both of them provide for longer periods of daylight autonomy but the orientation at 195° provided for more uniform daylight autonomy distribution and the maximum of % sensor points with daylight autonomy.

The daylight autonomy distribution and penetration due to the glazings on the facade was same on each floors of the buildings. This was not the case when an atrium was introduced. The lowest floors recorded the least daylight penetration and this increased with the floor level with top floor having the most daylight penetration.

The surrounding zones in the North of the atrium well saw a deeper daylight autonomy distribution. It was observed that the daylight autonomy distribution went deeper in all the zones surrounding the atrium which had a directional component towards the South. It was seen that the % of points with daylight autonomy did
not change significantly when the atrium was rotated. This was in contrast to the results obtained when daylight penetrated from the exterior glazings as the change in daylight autonomy distribution was significant as the building was rotated.

The author believes that the building oriented at 195° would provide for the best daylight autonomy distribution: uniform, more penetrating and the zones would remain daylight autonomous for a longer period of time. Also, the cooling loads associated at this orientation were the minimum.

The results that were collected in Appendix B can be used by the designer to see which parts of the building are daylight autonomous and which aren’t. Since the building had an open office space type, the results can be used to arrange the office spaces in such a way that certain tasks that are light intensive are carried out in the regions where these points are located. Even if the arrangement inside the office space goes through further designing and changes in later stages (usually is the case), the spaces can be arranged according to the daylight distribution data (color-mesh and % of sensor points with zero daylight autonomy) such that these spaces fulfill the daylighting requirements, if they are still important and the designer is still free to choose the orientation.

A more interesting thing to evaluate would have been to locate specific points inside the buildings which would stay autonomous for a certain period of time. For instance, knowing the location of the occupants working desk and locating points on it can give us information as to how long the occupant can work without the assistance of artificial light throughout the year. This data can be further used to determine the artificial light savings. But the information in regards to the occupant’s seating position was not available during the design process so this becomes a topic of further studies.

4.1 Future studies

The author believes that the results obtained can be further used in conjunction with more specific daylighting requirements to account for:

- Glare in the buildings caused by the sun when it is lower in the sky by choosing building specific shading options.

- The times during the year when overheating happens in the zones due to excessive solar gains and finding strategies to limit it to provide for better indoor climate.

- Excessive heat gains through the atrium roof glazing. The percentage of glazing used can be optimized to provide for the same daylighting performance without excessive heat.
Appendix A: Irradiation analysis results

A recipe was created in grasshopper using the ladybug tools to evaluate the amount of solar radiation that was received by the building body for two models: model without an atrium well and the model with an atrium well. A parametric analysis of the orientation was done to evaluate the solar radiations received by the models at different orientations. Both the models were rotated anti-clockwise about an axis passing through the centroid of the building with increments of 10 degrees and 15 degrees for a full circle.
(a) Irradiation analysis recipe as seen in Grasshopper.

(b) Building body without atrium well.

(c) Building body with atrium well.

(d) Model without atrium well: irradiation.

(e) Model with atrium well: irradiation.

Figure A.1: Irradiation analysis results.
(a) Total solar energy received by model without atrium well.

(b) Total solar energy received by model with atrium well.

Figure A.2: Irradiation analysis for both models at every 10° interval.
(a) Total solar energy received by model without atrium well.

(b) Total solar energy received my model with atrium well.

Figure A.3: Irradiation analysis for both models at every 15° increment.
Appendix B: Daylight Autonomy results

The appendix contains the results of the daylight autonomy for both model B (without the daylight from atrium) and model A (with daylight from atrium) at six orientations. A coloring scheme from blue to red was used to represent the daylight autonomy values. Blue corresponds to 0% while red corresponds to 100% daylight autonomy. The green points seen in the figures on the right corresponds to the sensor points which receive 0% DA.
B.0.1 Model images in Rhinoceros

Figure B.1: Building without atrium roof and interior glazing: model B.

Figure B.2: Building with atrium roof and interior glazing: model A.
B.1 Model B/0°/South-southwest

(a) DA: floor 0.

(b) Points with zero DA: floor 0.

(c) DA: floor 4.

(d) Points with zero DA: floor 4.

(e) DA on floor 7.

(f) Points with DA=0: floor 7.

Figure B.3: Daylight autonomy results: Model B/0°/South-southwest.
B.2 Model A/0°/South-southwest

Figure B.4: Daylight autonomy results: Model A/0°/South-southwest.
B.3 Model B/15°/South

Figure B.5: Daylight autonomy results: Model B/15°/South.
B.4 Model A/15°/South

(a) DA: floor 0.
(b) Points with zero DA: floor 0.
(c) DA: floor 4.
(d) Points with zero DA: floor 4.
(e) DA: floor 7.
(f) Points with zero DA: floor 7.

Figure B.6: Daylight autonomy results: Model A/15°/South.
B.5 Model B/60°/South-east

(a) DA: floor 0.
(b) Points with zero DA: floor 0.
(c) DA on floor 4.
(d) Points with zero DA: floor 4.
(e) DA: floor 7.
(f) Points with zero DA: floor 7.

Figure B.7: Daylight autonomy results: Model B/60°/South-east.
B.6 Model A/60°/South-east

Figure B.8: Daylight autonomy results: Model A/60°/South-east.
B.7 Model B/80°/East-southeast

Figure B.9: Daylight autonomy results: Model B/80°/East-southeast.
B.8 Model A/80°/East-southeast

Figure B.10: Daylight autonomy results: Model A/80°/East-southeast.
B.9 Model B/105°/East

Figure B.11: Daylight autonomy results: Model B/105°/E.
B.10 Model A/105°/East

(a) DA: floor 0.
(b) Points with zero DA: floor 0.
(c) DA: floor 4.
(d) Points with zero DA: floor 4.
(e) DA: floor 7.
(f) Points with zero DA: floor 7.

Figure B.12: Daylight autonomy results: Model A/105°/East.
B.11 Model B/195°/North

(a) DA on floor 0.
(b) Points with zero DA: floor 0.
(c) DA: floor 4.
(d) Points with zero DA: floor 4.
(e) DA: floor 7.
(f) Points with zero DA: floor 7.

Figure B.13: Daylight autonomy results: Model B/195°/North.
B.12 Model A/195°/North

Figure B.14: Daylight autonomy results: Model A/195°/North.
Appendix C: Cooling loads results

The appendix contains the two models that were simplified before the cooling load simulation were performed. The temperatures in the atrium zones are also included before and after the atrium roof glazing was introduced.
C.0.1 Model Images in IDA ICE

Figure C.1: Building model without atrium glazing as seen in IDA ICE: model B.

Figure C.2: Building model with atrium roof glazing as seen in IDA ICE: model A.
C.0.2 Temperatures in the atrium zone

Figure C.3: Temperatures in the atrium zone: model B.

Figure C.4: Temperatures in the atrium zone: model A.
Bibliography


