Daylight Optimization: A Parametric Study of Atrium Design

Early Stage Design Guidelines of Atria for Optimization of Daylight Autonomy

ÖRN ERLENDSSON

School of Architecture
and the Built Environment

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Royal Institute of Technology
SE 100–44 Stockholm

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School of Architecture and the Built Environment
Division of Building Services and Energy Systems

Supervisors: Ivo Martinac & Sarah Dahman Meyersson
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Kungliga Tekniska Högskolan /
Royal Institute of Technology
SE 100 – 44 Stockholm
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Approved:	Examiner:	Supervisors:
2014	Ivo Martinac	Sarah Dahman Meyersson Ivo Martinac
	Commissioner: White Arkitekter AB	Contact person: Sarah Dahman Meyersson

Abstract

This thesis investigates the design of atria for daylighting in large scale buildings. A three dimensional test building with a central atrium was constructed and various parameters of the atrium altered. The impact of these changes was studied through computer simulations of annual daylight distribution by implementing state of the art software. Daylight autonomy is simulated for an annual climate file for Stockholm, Sweden.

In the thesis, notion is made of basic daylighting concepts, the importance of bringing daylight into buildings is argued, and the daylighting criteria of three environmental certification tools introduced. Furthermore, a detailed comparison is made on several well known daylight simulation tools.

A newly developed, state of the art, daylight simulation tool called Honeybee, is used in the simulation process. The tool utilizes the calculation engines of well known daylight simulation software Radiance and Daysim, which apply backward ray-tracing to reach accurate results. Honeybee is coupled to the graphical algorithm editor Grasshopper for Rhinoceros 3D, which allows for an efficient way of parametric modelling.

The comparison of five different daylight simulation tools showed that Honeybee outweighs the capabilities of many of them by offering a wast range of simulation capabilities and also giving the user exceptional control of result data within multiple zones of the test building.

The results of the daylight study have been compiled into a document which purpose is to serve as early stage design guidelines of atria for architects. Many factors have been shown through simulation to have a dramatic impact on daylight on an annual basis, and several suggestions have been made on how to maximize the quantity of daylight within buildings containing atria.

Keywords

Atrium, daylight, daylight autonomy, dynamic daylight simulation, early stage design guidelines, Grasshopper, Honeybee, illuminance, optimization, parametric modelling

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White Arkitekter

White Arkitekter is a Scandinavian architectural practice founded by Sid White and PA Ekholm in Gothenburg, Sweden, in 1951. With over 14 offices in Sweden, Denmark, Norway and the UK, and over 700 team members, White has become one of the largest Scandinavian architectural firms. Ever since their founding days, their focus has been on raising the quality of every day life within a building, and that focus is clearly reflected in their design approach. Much effort is put into sustainable integrated design, innovation and energy-efficient solutions, which keeps the company on the forefront of sustainable architectural design. [5] White Arkitekter has proposed the topic of this thesis study to gain additional information of daylight to aid them in their design process of large scale buildings.

Glossary

Analysis plane: See workplane.

Annual sunlight exposure: The percentage of floor-area that has direct sunlight (>1000 lux) for more than 250 hours per year. [55]

Atrium: An atrium (pl. atria) is usually a large and multistoried, glass-roofed room used to bring daylight to the interior of thick buildings where sidelight alone cannot penetrate. The atrium may be enclosed on two, three, or four sides by the rooms it helps light. [8]

Atrium well: The space which is enclosed by the boundary surfaces of an atrium (i.e. walls, floor, and roof).

BREEAM: Environmental certification developed by the British Research Establishement (Bre) that stands for Building Research Establishment Environmental Assessment Methodology

CIE: Commission Internationale De L'Eclairage *(e. International Commission on Illumination)* [38]

CIE standard overcast sky: A completely overcast sky for which the ratio of luminance at an altitude q above the horizon to the luminance at the zenith is assumed to be $(1 + 2 \sin \mathrm{q})/3$. This means that the luminance at the zenith is three times brighter than at the horizon. [8]

Daylight: Light received from the sky either as direct light from the sun or as diffuse daylight scattered in the atmosphere.

Daylighting: Daylighting is the controlled admission of natural light (i.e. direct sunlight and diffuse skylight) into a building to reduce electric lighting and save energy. [2]

Daylight autonomy: A percentage of annual daytime hours that a given point in a space is above a specified illumination level. [35]

Daylight factor: The ratio which represents the amount of illumination available indoors, relative to the illumination present outdoors at the same time under an unobstructed CIE standard overcast sky. [35]

Daylight metrics: A metric refers to the scale created by a complete set of daylight measurements. Metrics can be defined by one basic calculation or a combination of calculation methods. [25]

Grasshopper: A generic algorithm editor which allows the user to perform parametric modelling directly within the 3D modelling tool Rhinoceros.

Illuminance: The amount of light falling on a surface per unit area, measured in lux [15]

LEED: Environmental certification developed by the US Green Building Council that stands for Leadership in Energy and Environmental Design

Luminance: The amount of light energy emitted or reflected from an object in a specific direction. Luminance is the only form of light we can see. [19]

Natural light: See daylight.

Occupied space: A room or space within the assessed building that is likely to be occupied for 30 minutes or more by a building user. [15]

Parametric design: The automated parameter-based generation of architectural elements. [4]

Scripting: Scripting refers to the action of writing in a programming language.

Spatial daylight autonomy: The percentage of area in a building that is above a certain threshold illuminance value for 50% of the annual occupancy time. [55]

Task plane: See workplane.

Uniformity: The ratio between the minimum illuminance (from daylight) on the working plane within a room (or minimum daylight factor) and the average illuminance (from daylight) on the same working plane (or average daylight factor). [15]

View of sky: Areas of the working plane have view of sky when they receive direct light from the sky. [15]

Workplane: An imaginary horizontal plane on which a task is performed and daylight is measured. Generally defined 0.7 – 0.85 m above floor depending on the certification system being used. Also referred to as working plane, analysis plane or task plane within the content of this thesis.

Zenith: The top of the sky dome. A point directly overhead, 90° in altitude angle above the horizon. [8]

Nomenclature

ΔS	*Angular size of sky segment*	[m^2]
ASE	*Annual Sunlight Exposure*	[%]
cDA	*Continuous daylight autonomy*	[%]
DA	*Daylight autonomy*	[%]
DF	*Daylight factor*	[%]
DC	*Daylight component*	[–]
DDS	*Dynamic daylight simulations*	
E	*Illuminance*	[lux]
L	*Luminance*	[cd/m^2]
R	*Radiance*	[W/m^2]
R_{eff}	*Luminous efficacy*	[lm/W]
sDA	*Spatial daylight autonomy*	[%]
S	*Size of sky segment*	[m^2]
UDI	*Useful daylight illuminance*	[%]

"No space, architecturally, is a space unless it has natural light" – Louis Kahn

Contents

List of Figures

List of Tables

Chapter 1: Introduction

1.1 Introduction

In ancient Roman times, the atrium was the central open area of a house, admitting light and air to the surrounding dwelling space [54], but today the term atrium is typically associated with commercial or public buildings in which the atria are commonly used as key architectural features in main entries, public circulation areas or as special destinations within a building. [11]. In fact, many of today's large scale buildings are designed with atria.

An *atrium* (pl. atria) is is usually a large and multistoried, glass-roofed room used to bring daylight to the interior of large buildings where sidelight alone cannot penetrate. The atrium may be enclosed on one, two, three, or four sides by the rooms it helps light. [8] The function of the atrium offers many practical uses for a building such as a source for natural ventilation which can help maintain thermal comfort, a buffer space to reduce energy losses and consumption, and to introduce daylight into the core of the building. This multi functionality of the atrium is what makes it a complex object, worthy of investigating.

> *There are many reasons to daylight buildings, both subjective and objective. Though the measurable energy savings, light quality, and environmental benefits of daylighting in buildings are undisputed, there are other equally compelling reasons supporting daylighting. Light is not merely the revealer of form. Its rhythms are fundamental to life. Light resets our biological clocks every day and plays a role in many human biological and psychological processes. The way architecture admits light places us in relationship with sky and horizon, giving to varieties of human interpretation and meaning. Light's cycles, the day's length, the sun's intensity, the seasonal patterns of sky cover, the dawn-to-dusk solar arc, are the most fundamental presence of nature in our lives.* [18]

In the above quote, architect and professor Mark DeKay highlights the various aspects of natural light in buildings. The focus of this thesis will be on the daylighting aspect and how various parameters influence the distribution of light from the atrium and into the adjacent spaces, and what to consider when designing for daylighting access at an early stage in the design process.

1.2 Background

Using daylight as part of an integrated and controlled lighting strategy is a key component of a sustainable, environmental approach to architectural design. An atrium is potentially a major source of daylight for deep plan buildings and offers other environmental benefits in terms of solar gain, reduced energy losses and natural ventilation. [61] Even more so, one of the most cost-effective ways to reduce energy consumption in non-residential buildings is the replacement of electric light, which contributes about one-third of the commercial building energy use, with daylight. [18]

Bringing natural light into buildings is therefore one of the many key features of a sustainable building and most environmental building certifications award credits for daylighting levels. Designing atria to reach an optimum level of natural light within a building can however be tricky due to the many parameters which influence the light distribution. The benefits of atria can therefore vary quite a lot. White Arkitekter sees this issue as a potential for adding knowledge to their artillery and has thus proposed the study related to this thesis.

Considerable time and money can be saved by providing architects with guiding principles on the design of atria from the very beginning of a project, which greatly increases the potential for an optimized solution. More attention can then be given to more detailed matters, resulting in a higher quality outcome

Many different daylight simulation programs are available to designers, but they can be quite cumbersome and therefore difficult to implement at an early stage in the design process. With the help of parametric design, this optimisation process has been made quite accessible to the experienced designer.

The goal with this thesis is therefore to explore the aspect of daylight and the atrium, and create guidelines, which will be accessible to architects and engineers to help them design effective atria from the very start of the project, and therefore increase the quality of architectural design practices regarding daylight access. Important questions concerning the design of atria will be answered through parametric studies of 3D models using *Grasshopper* for Rhinoceros and both static- and dynamic daylight simulations with *Honeybee* for Grasshopper[1].

[1] Descriptions of the software are given in section 2.1

1.2.1 Limitations

The study is limited by the extensive calculation time which is required to obtain high quality results for large scale building models with daylight simulation. This had an effect both on the size and complexity of the model, as well as the resolution of the results. The author also did not have prior knowledge of the simulation and modelling tools used in the study, which meant that a lot of time was associated with familiarising with the aforementioned tools.

1.2.2 Expected outcome

The expected outcome of the thesis is a document, containing answers to proposed study questions, results from simulations, and other relevant information. The document will be formulated as guidelines for early stage design of atria for daylight autonomy optimization. The document will be made available to architects at White Arkitekter. Furthermore, a document with assessment of different daylight simulation tools will be made available for experts at White Arkitekter. At the end of this study, the author will also have obtained good knowledge of the simulation and modelling tools used in the thesis work, and he will be able to apply the tools in his future work.

1.3 Literature review

User satisfaction in buildings depends to a large extent on lighting comfort. A higher proportion of natural light is conductive to good health and productivity in the work place. Moreover, a high level of daylight autonomy also results in a reduction of the running costs. Questions relating to lighting can be resolved at an early stage during the design phase with the help of daylight simulation. [33] The following text is devoted to research and literature related to the content of this thesis.

Sharples and Lash (2007) concluded in their critical review on daylight in atrium buildings, that a major component of the environmental and sustainable solutions to the energy performance of a buildings is the replacing or supplementing of artificial lighting use by daylight. [61] But how does a designer achieve this in atria buildings in an efficient way? For daylight design, the key atrium components are the roof fenestration system, the geometry of the atrium well, the reflectance of the well's surfaces and the daylight levels achieved in spaces adjacent to the well. [61] The daylight levels in these spaces are influenced, not only by the aforementioned parameters, but also by the access of daylight to the spaces. Cole (1990) studied a 5-storey atrium well and found the percentage of opening configuration of ground – 100%, 2$^{\text{nd}}$ – 80%, 3$^{\text{rd}}$ – 60%, 4$^{\text{th}}$ – 40%, and 5$^{\text{th}}$ – 20% to be most effective. [12]

In their assessment on daylight factor predictions in atrium building design, Calcagni and Paroncini (2004) came to the conclusion that increased reflectance values of atrium surfaces does not produce a significant improvement in the daylight factor levels on the atrium's ground floor, due to the large extension of openings and windows with high transmittance within the atrium wells. Surfaces that could potentially reflect light are very limited and therefore have negligible effect on the daylight factor. [9] This coincides with Cole's discovery, i.e. decreasing the area of openings on the upper levels of the atrium well offers more surface area for the light to bounce off and down into the well. This was also verified by Aschehoug (1986), who found that having smaller windows on the top floors of the atrium well results in more light being reflected by the atrium facade. [6]

Cole also stated in his study that increasing the reflectivity of the ground floor of an atrium has significant effect in raising the daylight levels in adjacent spaces at that level. [12]

Du and Sharples (2010) performed a comparative study of the vertical sky component with physical measurements on a scale model and computer generated daylight simulations on a 3D model using the ray-tracing program Radiance. Their results showed that measured values from the scale model compared well with the simulated data. [21] In fact, in recent years more and more attention has been given to daylight simulation software as daylighting has become an important part of sustainable/green buildings certification credits, and it is difficult to evaluate the quality and quantity in a space through simple rules of thumb. [57]

Reinhart and Fitz (2004) made an online survey on the use of daylight simulation programs. The survey, with 193 participants (from various countries) in the field of architecture, engineering, daylight design consulting and academic researches, showed that, of the 134 participants that used computer simulation tools for daylighting design, a total of 42 different daylight simulation software were listed. Most popular was the RADIANCE tool or RADIANCE-based tools. [57]

In their book on daylight design, N. Baker and K. Steemers (2013) state that there are three components most critical to daylighting the rooms adjacent to an atrium well, i.e. light from the sky, light reflected from the atrium walls and light reflected of the atrium floor. At the lower levels of an atrium, the reflected sources of light become even more crucial as the angle to the direct sky increases. It is therefore very important to have high reflectance values on these surfaces, as well as the ceilings of the adjacent spaces. [7]

In a daylight building design guide published by the *European Directorate-General for Energy*, many design principles for daylight optimisation are mentioned, one of which is the benefits of implementing light shelves to redirect incoming light onto the ceiling and simultaneously provide shading for the area of the room close to the window. They also mention that the underside of the light shelf can redirect light from a high-reflectance exterior ground surface onto floor inside the room, and that a light shelf is most efficient when it is external, causes minimal obstruction to the window area, has specular reflective surfaces, and is combined with a ceiling of high reflectance. Moreover, they state that internal light shelves have not been found to be as effective as they obstruct daylight entering the room while providing little compensating benefit. [51]

R. Saxon (1986) mentions in his book *Atrium Buildings – Development and Design*, that there is a trade-off between plan depth and storey-height within an overall volume, and that raising ceiling levels from 2.7 m to 3.6 m can allow good light up to 9 m into the plan. [60]

It is evident from the literature reviewed that there are many parameters which influence the distribution of daylight within buildings and many tools are available for design and simulation. The above literature review merely shows some of the literature which helped decide which parameters to study in context of this thesis. This study aims to verify the effect of the parameters introduced in the literature as well as presenting additional parameters of interest. The thesis also aims to locate a user friendly simulation tool, well suited for simulating daylight within atria and their adjoining spaces while also providing good integration with the 3D modelling tool.

1.4 Basic concepts of daylight

In the following section, a few concepts, used throughout this thesis and common to the study of daylight, are explained. More concepts are introduced in later context.

1.4.1 Sources of daylight

Daylight sources can be identified into two categories of direct- and indirect daylight. *Direct daylight* is the light received from diffuse skylight from the earth's atmosphere or direct sunlight, and *indirect daylight* is the light received from reflective surfaces such as pavement in front of a window or a wall opposite to a window. [62] Designing buildings with higher glazing ratios on southern façades will allow more direct daylight to enter a building, thus offering the possibility of, for example, winter heating and a brighter environment, but simultaneously increasing the risk of over-heating in the summer, and risk of glare. Designing an atrium with a broad view of the sky will allow both direct- and diffuse daylight to enter the building, while designing the surfaces of an atrium well to maximise the reflected component of daylight will increase the benefit of the indirect daylight at lower levels of the atrium. The upper parts of an atrium relies on direct daylight, while the lower parts of an atrium rely mainly on indirect reflected daylight. [60]

1.4.2 Reflectance and transmittance

When light strikes a surface it is either reflected, transmitted or absorbed. The reflectance factor is given in the range of 0 to 1 and it defined as the "ratio of reflected flux to incident flux". It determines how much of the light is reflected, while the transmittance gives a measure of the fraction of light that passes through a surface. Lastly, the light absorbency of a surface gives a measure of how much light is absorbed by a surface. The absorbed light is generally transferred into heat. A surface will always reflect some light. For instance, a white surface has a reflectance factor of 0.85 and a black surface has a value of 0.5. The reflectance of a surface cannot be used to determine how the light is reflected, only how much. The surface characteristic will determine how the light is reflected. For example, a very smooth polished surface will produce specular reflections, while matte surfaces will scatter the light to produce diffuse reflections. The light we rely on to reach the adjacent spaces of an atrium well, especially at the lower levels, is mostly indirect light reflected of the atrium surfaces, as the view to the sky is limited. Choosing surfaces with good reflectance but low specular values (to reduce risk of glare) will thus help to introduce light deep into a building. Furthermore, the light quantity in those adjoining spaces depends on the percentage of light the glazing, which the light passes through, transmits. [40, 62]

1.4.3 Illuminance and luminance

The total light emitted by a source is known as the luminous flux, given in lumens (lm). The intensity of the light source, i.e. the luminous intensity is given in candela (cd) and specifies the intensity of the light in a given direction. The measure of this intensity over a surface is called Illuminance. Illuminance is thus the amount of light energy in a given reference point on a defined surface area, given in the unit of lux. Illuminance is light passing through space and is invisible to the naked eye unless directly observed at the source or on a surface it reflects off. This observable portion of light on a surface is known as luminance, which is defined as "*the amount of visible light leaving a point on a surface in a given direction*", given in cd/m^2. Luminance therefore gives us an indicator of the brightness of light received by the viewer, and the illuminance gives us an indicator of the presence of light within a space. [19, 40, 47, 62] To give the reader an idea of typical illuminance values, examples of recommended illuminance values are given in table 1.1.

Table 1.1: Examples of recommended illuminance values, as stated in the standard EN-12464, of typical zones and activities. [36]

Activity	**Area**	**Illuminance [lux]**
Casual seeing	Corridors, changing rooms, stores	100
Some perception of detail	Loading bays, switching rooms	150
Continuously occupied	Entrance halls, dining rooms	200
Easy visual tasks	Libraries, sports halls, lecture halls	300
Moderately difficult visual tasks	General offices, kitchens, laboratories, retail shops	500
Difficult visual tasks	Drawing offices, sculpture work	750
Visual tasks very difficult	Examination and treatment (healthcare), supermarkets	1000
Extremely difficult visual tasks	Small scale detail work and inspection, precision assembly	1500
Performance of very special visual tasks	Operation rooms (healthcare), fine detail inspection areas	>5000

1.4.4 Qualitative and quantitative aspects of daylight

A good daylighting[2] strategy should have just as much focus on the quality of light as it does on the quantity of light within a space. In a design brief from the *Architectural Energy Corporation* on understanding daylight metrics[3], the quantitative and qualitative aspects of daylight are defined. Metrics such as illuminance, the

[2] *"Daylighting describes the act of lighting the interior of a building with daylight. The term is predominantly used in the context of commercial buildings in which the time of daylight availability and building occupation largely overlap. The objectives of daylighting are to enhance visual comfort conditions for building occupants and to reduce the overall energy use of the building."* [56]

[3] *"A daylight metric refers to the scale created by a complete set of daylight measurements. Metrics can be defined by one basic calculation method or a combination of calculation methods."* [25]

daylight factor, and various daylight autonomy hybrids are used to give a general sense of the daylight quantity while the qualitative aspects of daylight are defined by metrics which shape the luminous environment, or in other words, metrics which give a sense of how we perceive light within a space. For example, the colour, contrast and temperature of light within a room, or the uniformity of light within a room all affect the comfort of the occupants of a daylit space.

In a paper titled *Conditions Required for Visual Comfort* by Calleja et al. (2011), various aspects of the luminous environment are presented. An important aspect of how people experience light within a space is by the colour of the light chosen for an application. The colour and temperature of light within a room is of course very important and should generally be maintained at levels which do not cause discomfort or strain on the eyes of occupants performing tasks within the room. *"The colour appearance of illumination depends not only on the colour of light, but also on the level of luminous intensity. A colour temperature is associated with the different forms of illumination."* In the paper, a diagram[4] showing the relationship between visual comfort and different levels of illumination and colour temperature is given. The diagram illustrates that there is a relationship between comfortable illumination levels and colour temperatures. Quite noticeable is the satisfactory appearance of illumination levels above 4000 kelvin (K). This colour temperature is typically defined as neutral white, while levels around 6000 K are defined as daylight white. [30]

The contrast of light within a room is also important. The *contrast* of light within a space represents the ratio of background light to foreground light, where background light (or ambient light) is the light which provides a space with background illumination and foreground light (or task light) is the light needed to provide the right level of sharpness within a room. Mathematically, contrast of light is expressed in terms of the difference of maximum and minimum luminance divided by the lower value. Generally, to ensure good quality contrast levels in a space, ambient light levels should be kept within the range of one-half and two-thirds of task light. [47, 60]

Maintaining certain uniformity values is just as important. The *uniformity* of light within a space is determined by the ratio between the minimum illuminance (or daylight factor) value and the average illuminance (or daylight factor), both of which are measured over a horizontal working plane within a space. Keeping a good uniformity of light means reducing high intensity zones of daylight over the workplane[5] while also ensuring that dark zones do not appear, generally in the back of a room. High intensity zones of daylight, whether they appear on the workplane

[4] The diagram is not given here due to copyright reasons. To view the diagram go to the source: http://www.ilo.org/oshenc/part-vi/lighting/item/284-conditions-required-for-visual-comfort

[5] *Workplane* refers to the imaginary horizontal plane on which a task is performed. Generally defined 0.7 – 0.85 m above floor depending on certification (see section 1.6). Also referred to as working plane, analysis plane or task plane within the content of this thesis.

or on the floor or even on the walls or ceiling, can cause discomfort to occupants. This is generally known as glare. More precisely, *glare* is the *"condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or to extreme contrasts."* [22] Glare caused by daylight can usually be controlled with the proper implementation of shading devices, which should be installed in such a way that they do not cause patches of light (dark or bright) over the workplane as that will most likely irritate occupants.

1.5 Benefits of daylight in buildings

As has been mentioned several times, atria are key components in bringing natural light into deep-plan buildings, but what are some of the benefits of bringing daylight into buildings? The purpose of daylighting is pretty well highlighted in the daylighting chapter in the LEED certification[6]. It states: *"the intent of the daylighting chapter is to connect building occupants with the outdoors, reinforce circadian rhythms, and reduce the use of electrical lighting by introducing daylight into the space."* [16] To better understand the importance of good daylight in a building, one must locate it in relation to sustainability. Three aspects, environmental, social and economic, all related to sustainability, are highlighted in the following sections to help explain the benefits of bringing daylight into a building.

1.5.1 Environmental aspect

One important aspect to environmentally concious design is allowing for the reduction of artificial light in a building by introducing daylight into it. To put in perspective the amount of artificial lighting in use by today's society, one can simply look at the electricity consumption of this light source. The *International Energy Agency* states that artificial lighting represents almost 20% of global electricity consumption, which is similar to the amount of electricity generated globally by nuclear power on an annual basis. [24] Not only is the use of energy resources immense, artificial lighting systems also come with a great deal of waste. In an article on *environmental repercussions of artificial lighting*, Páramo (2008) highlights three forms of waste produced by artificial lighting, in terms of material waste (bulbs and the lighting system), energy consumption (heat, UV and electromagnetic radiation), and light pollution. [53] The excessive heat produced by artificial lighting systems increases the cooling loads on the mechanical cooling system of a building. Reducing the usage of artificial lighting can potentially reduce building cooling loads by 10–20%.[2] Reducing the energy consumption of a building by implementing daylighting strategies creates potential for reducing carbon dioxide emissions, which ultimately reduces greenhouse effects.

[6]LEED is an American environmental certification which stands for *Leadership in Energy and Environmental Design*

1.5.2 Social aspect

By introducing daylight into deep plan buildings, occupants are provided with a sense of orientation, time, weather and the world outside the building.[54] Furthermore, the presence of natural light has been shown to have positive effect on human health, productivity and our biological clock. The biological clock, which regulates our sleep-wake cycle (or circadian rhythms), is primarily controlled by the brains production of melatonin, which is produced whenever people are in the dark. Research has shown that bright light (> 1500 lux) through the eyes will cause the pineal gland in the brain to stop making melatonin. High melatonin levels cause drowsiness, while low levels produce alertness; thus, melatonin plays a critical part in controlling our circadian cycles. A similar research, made by Dr. Alfred J. Lewy, showed that light therapy could help some patients who became depressed during the short winter days, as it had an effect on their melatonin levels. In a literature review on the effects of natural light on building occupants, Edwards and Torcellini (2002) present several researches showing increased productivity of office workers in spaces with natural light or view through a window. In their literature review, they also state that natural light increases attention and alertness during the post-lunch dip and has shown to be helpful in increasing alertness for monotonous work. Mention is also made of the decreased recovery time of patients in hospitals and reduced stress of doctors and nurses. Furthermore, Edwards and Torcellini present several studies conducted on academic benefits of daylighting. Improved test scores, faster learning rates by 20–26%, improved attendance by 1.6–1.9% and better behaviour are just some of the academic benefits of daylighting mentioned in their study. [23, 29, 40]

1.5.3 Economic aspect

By introducing natural daylight into a building, less electricity is needed to power a comfortable lighting zone, while fewer artificial lights in a zone also means that excessive heat, generated by the lighting system, becomes lower, which in turns lowers the cooling load on the mechanical cooling system. All of this results in a lower energy bill. The US National Institute of Building Sciences estimates that the total energy costs of a building can be reduced by one third through optimal integration of daylighting strategies. [2] Not only is the energy bill lowered, but a smaller artificial lighting systems consequently means that the use of materials is reduced and cost of maintenance also becomes lower.

In a recent study conducted by the *British Council for Offices* (BCO), on *the impact of office design on building performance*, it is estimated that the cost of employee salaries accounts for roughly 85% of office building operations cost over a 25 year running period. The other costs accounted for in BCO's study are microscopic in proportion to the cost of employee salaries. The financial impact of stimulating office worker productivity is therefore far greater than any financial saving strategy that might affect any of the other factors. The study also mentions that an increase in productivity of 3–20% of office workers can be found relating to good lighting design and adequately daylit environments, hence highlighting the financial importance of a well daylit environment. [49]

1.5.4 Summary

The impact a good daylighting strategy can have on a building and its occupants has proven to be a critical component of sustainable design. With poor daylight levels the physiological and psychological experience of building occupants is not nearly as good as in a well daylit environment, and the overall mental state and health of occupants is greatly influenced by the presence of natural light. Furthermore, within a poorly lit space the need for artificial lighting is raised, which increases energy demand and thereby raises the electricity bill. One should however keep in mind that the benefits of daylighting will only be realized if implemented correctly. If a daylighting strategy is poorly integrated into a building it can result in the exact opposite of its intended purpose. Excessive levels of daylight can reduce productivity and increase employees absenteeism due to the possibility of extremely high lighting levels, excessive glare, and temperatures. [23]

1.6 Daylight in standards and certifications

The American rating system *LEED*[7], the British rating system *BREEAM*[8], and the Swedish rating system *Miljöbyggnad* for buildings according to Swedish building regulations, are three different environmental certification systems which present various criteria for designing environmentally responsible buildings, one of which ensures that daylighting prerequisites are met within the occupied spaces of a building. Additionally, several standards exist to aid designers in daylight design.

1.6.1 Swedish standards

Currently there are three Swedish standards with recommendations on daylight, Boverket's Building Regulations (BBR), the Swedish version of the European standard EN 12464-1[9], and the Swedish standard SS 914201.

BBR only provides a very short chapter with some general recommendations on daylighting and mainly refers to the SS-EN 12464-1 and SS 91 42 01 standards. SS-EN 12464-1, on the other hand, gives general recommendations of luminance and illuminance values, and reflectance values of surfaces within a work-place environment, as well as giving definitions on daylighting concepts and equations. Table 1.2 gives the recommended reflectance parameters of important surfaces as presented in the Swedish standard SS-EN 12464-1. Lastly, SS 914201 presents a simplified method for checking required window glass area of side lit rooms. The method presented in this standard can be used when the light transmittance of the glazing being used is better than that of three clear panels, or daylight at the location defined in Miljöbyggnad (see section 1.6.2) is not obstructed by a certain amount[10].

Table 1.2: Suitable reflectance of important surfaces as presented in EN 12464-1:2002 [36]

Surface	Reflectance
Ceilings	0.6 – 0.9
Walls	0.3 – 0.8
Floors	0.1 – 0.5
Work planes	0.2 – 0.6

1.6.2 Miljöbyggnad

Miljöbyggnad, which amongst other criteria, presents rating criteria on the daylight quantity within a space by giving a method of measuring the daylight factor (DF) within the space, at half the room depth, one meter from the darkest wall and

[7] LEED is developed by the US Green Building Council (USGBC), and stands for *Leadership in Energy and Environmental Design*.

[8] BREEAM is developed by the British Research Establishment (BRE) and stands for *Building Research Establishment Environmental Assessment Methodology*.

[9] The current Swedish version has the name SS-EN 12464-1:2011 Ljus och belysning – Belysning av arbetsplatser // Light and lighting – Light of work places.

[10] See SS 914201 standard for more detail.

0.8 m over the floor.[11] Ratings are given in terms of bronze (DF $\geq$ 1.0%), silver (DF $\geq$ 1.2%) or gold (DF $\geq$ 1.2% plus a survey with >80% satisfaction). When rating is given, half of the area which complies to 20% of the heated area within the building is allowed to be one level below the required value. Alternatively, the certification allows the method presented in SS 91 42 01 to be used when the requirements stated in the standard are fulfilled. [14]

1.6.3 BREEAM

In BREEAM it is not enough to satisfy only one criterion, instead a combination of two criteria must be fulfilled. The certification presents methods of measuring the daylight factor, average daylight illuminance, uniformity, view of sky from desk height, and the room depth criterion. For example the certification defines a zone to be adequately daylit if 80% of the floor area receives an average daylight illuminance of 200 lux for 2650 hours per year or an average daylight factor in accordance to specific values based on different latitudes. In addition to either of these criteria, a specific uniformity ratio must be reached or a specific point daylight factor in accordance to specific values based on different latitudes. Alternatively, daylighting points can also be reached by achieving a view of sky from desk height[12] and satisfying the room depth criterion, defined as

$$\frac{\mathrm{d}}{\mathrm{w}} + \frac{\mathrm{d}}{\mathrm{HW}} < \frac{2}{(1 - \mathrm{RB})} \tag{1.1}$$

where

d = room depth,

w = room width,

HW = window head height from floor level,

RB = average reflectance of surfaces in the rear half of the room.

Lastly, the standard requires designers to assess the need for glare control with shading systems and also introduces an outline for exemplary level criteria for innovation credits as well as defining a schedule for required evidence of fulfilled criteria. [15]

1.6.4 LEEDv4

In its latest version, LEED presents criteria for dynamic assessment of daylight quantity and quality through computer simulations. The criteria for good daylight can be achieved through one of three options introduced in the certification. In

[11]The height 0.8 m is used because it represents a typical desk height.

[12]Desk height is defined as 0.7 m for offices and 0.85 m for industry in BREEAM.

the first option, annual computer simulations must be performed to show that certain levels of spatial daylight autonomy[13] and annual sunlight exposure[14] (ASE) are obtained on specific floor areas. The second option requires the designer to demonstrate through computer modelling that illuminance levels will be between 300 and 3000 lux for 9 a.m. and 3 p.m., both on a clear-sky day at the equinox for specific floor areas. The last option requires illuminance levels between 300 and 3000 lux for specific floor area during any hour between 9 a.m. and 3 p.m. for an appropriate work plane height. For this option, two measurements need to be taken as specified in the certification. [16]

1.6.5 Summary

The three aforementioned certifications all offer different ways of verifying daylight availability and quality. Miljöbyggnad offers perhaps the most simple method of assessing the daylight within a space, while LEED and BREEAM present a more complex method in the form of dynamic daylight evaluation. The method of daylighting assessment presented in Miljöbyggnad, by way of the daylight factor, has in recent years been argued to be obsolete, the reason being that it is calculated under a CIE standard overcast sky[15], therefore not offering the possibility of predicting the daylighting quality and quantity during various weather and sky conditions on an annual basis. [20] In the literature studied, the most common daylight metric was the daylight factor, most likely due to the simple method of calculation, but also due to the fact that computational power of every day computers has only recently become powerful enough to handle the heavy calculations required for dynamic daylight simulations. An explanation of the benefits of doing dynamic evaluations as opposed to static evaluations in the form of the daylight factor method are given in section 2.10.

[13] *Spatial daylight autonomy* (sDA) is the percentage of area that is above 300 lux 50% of the time or more during annual occupancy hours for a certain percentage of floor area. The threshold for the sDA floor area is set as 55%, 75% or 90% depending on the room type and number of certification points awarded. [16, 55]

[14] *Annual sunlight exposure* is the percentage of floor area that has direct sunlight (> 1000 lux) for more than 250 hours over the course of a year. [55]

[15] Sky types are explained in section 2.8.

Chapter 2: Methodology

2.1 Simulation software and modelling tools

Due to the complexity and size of the simulations performed in this study, it was very important to choose tools which allowed for smooth integration between modelling tool and simulation tool. The author therefore made an assessment of five different simulation tools and evaluated them in terms of various factors, such as user interface, simulation capabilities, integration with modelling tool, and data manipulation. The results of this software assessment are given in appendix A, along with a comparative table of the different tools. This section offers an overview of the main applications and tools implemented in the thesis study.

2.1.1 Rhinoceros

Rhinoceros (often abbreviated as *Rhino*) is a 3D modelling tool capable of creating and analysing complex geometry. Modelling capabilities are nearly endless, and offer the possibility of generating anything from simple curves, lines and shapes, to complex NURBS-curves[16], point clouds, and polygon meshes. [46] Rhino can be coupled with a generative algorithm extension called Grasshopper which can be used for modelling and analysis within Rhino. This algorithm extension was used in relation to this thesis for both modelling and simulation.

2.1.2 Grasshopper for Rhino

Grasshopper is a free, state of the art, graphical algorithm editor which serves as a parametric modelling extension to Rhino. *Parametric design/modelling* refers to the automated parameter-based generation of architectural elements. This means that the generation and alteration of elements within a project is controlled with specific algorithm generated rule-sets. Elements are automatically drawn based on user-defined algorithms and by changing parameters within the algorithm, a design can be easily controlled. [4] Grasshopper thus allows the user to easily manipulate the dimensions of models by defining form-generating components, which can be optimised through the use of sliders and mathematical expressions as shown in

[16] *NURBS: "Non Uniform Rational B-Spline, are mathematical representations of 3D geometry that can accurately describe any shape, such as simple 2D lines, curves, or 3D free-form surfaces or solids."* [46]

figure 2.1, or even with scripting. The Grasshopper interface is directly connected to the Rhino modelling tool so that changes made in the Grasshopper algorithm can be directly observed in the Rhino window, as shown in appendix E.

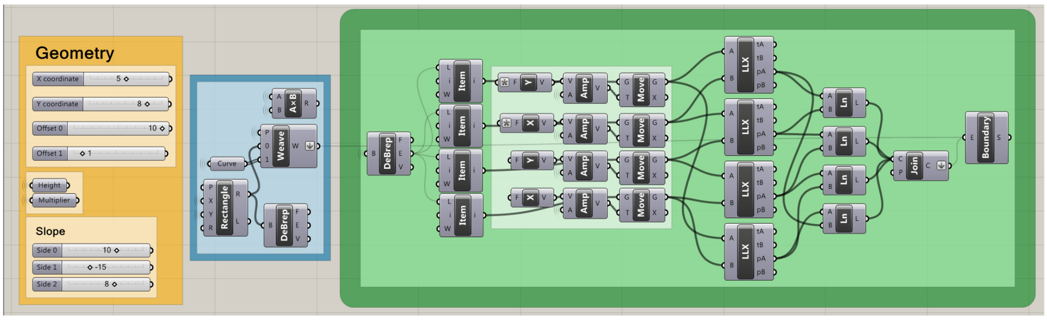


Figure 2.1: Form generating components are connected together in the Grasshopper interface to control dimensions of 3D models.

2.1.3 Honeybee for Grasshopper

Honeybee, developed by Mostapha S. Roudsari, is a free and open source, state of the art, environmental plugin which connects Grasshopper to EnergyPlus, Radiance, and Daysim for daylight simulations [17]. The plugin allows the user to create geometry and generate Radiance-materials[18] and skies. Honeybee appears as a tab in the Grasshopper interface, and since Honeybee is connected to Grasshopper, simulation results can be viewed directly within the 3D model in the Rhino interface. By storing results in csv-files[19], design alterations to the building model in Rhino can be coupled with the resulting daylight simulation data. The results can therefore be viewed instantaneously within the model as it is altered in the Grasshopper interface. Since Honeybee uses both Radiance and Daysim, static simulations can be carried out for one sky condition at a time for a single point in time with Radiance, or alternatively, annual illumanance profiles can be calculated based on specific climate files and geographic locations with Daysim. [59]

2.1.4 Radiance

Radiance, developed by Greg Ward at Lawrence Berkeley National Laboratory, is an advanced lighting simulation and backward ray-tracing [20] rendering package which simulates indoor illuminance and luminance distributions due to daylight for complex building geometries and a wide range of material surface properties for one sky condition at a time. [50, 56]

[17] EnergyPlus is an energy analysis and thermal load simulation program [50].

[18] Radiance-materials are materials with user defined characteristics which define how a surface reacts to light. Characteristics such as reflectance, light transmittance, roughness and specularity can be easily defined.

[19] A CSV-file refers to a comma-seperated-value file used for storing plain text such as numeric data or text.

[20] Rayt-racing and Radiance parameters are explained in section 2.13

2.1.5 Daysim

Daysim, developed at Harvard University and coordinated by Christoph Reinhart, is a validated daylight simulation tool based on Radiance's daylighting algorithm. The tool adds capabilities for efficiently calculating annual indoor illuminance/luminance profiles based on weather climate files, which can then be further coupled with user behaviour models for predicting daylight performance indicators. [28, 34, 56]

2.1.6 Matlab

"Matlab® *is a high-level language and interactive environment for numerical computation, visualization, and programming. Using* Matlab, *the user can analyse data, develop algorithms, and create models and applications. The language, tools, and built-in math functions enable the user to reach a solution faster than with spreadsheets or traditional programming languages."* A script, presented in appendix G, was written in Matlab to plot and evaluate the results from the Honeybee simulations. [45]

2.2 Standard model & assumptions

A standard model, illustrated in figure 2.2, was used as a starting point for all simulations in this study. Parameters, such as glazing ratios, atrium depth, height and length, floor plan depth, and number of floors were set to represent the information gathered in the literature review. Since the model was created using Grasshopper, these parameters could easily be altered for each and every simulation. The following section describes the standard model.

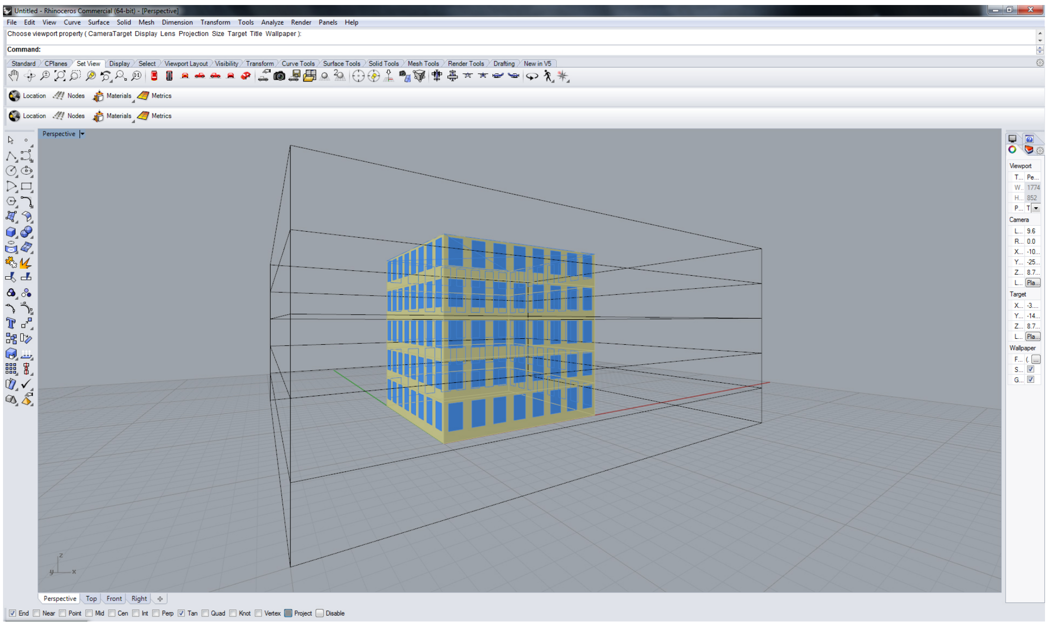


Figure 2.2: The standard model which was used as a basis for all simulations in this thesis. In the figure, the central atrium is viewed through a transparent façade and transparent floors.

A central atrium presents the greatest difficulty of bringing daylight into the lower floors of a building. A central atrium was therefore implemented in the standard model.

Glazing-to-wall ratios (GWR) were set to 40% in the base model. This was done in accordance to a article by Flodberg et al., in which they state that GWR values higher than 40% have negligible effect on daylight within buildings, and no electric lighting will therefore be saved. [31]

In a thesis by Mabb and an article by Yi, the positive effect on daylight in adjacent spaces of atria with low well index[21] is argued. This is similar to what Swinal mentions in his thesis, i.e. a low well index means that the atrium is shallow and wide in proportion to its height and thus offers more light to the atrium and its adjoining spaces. [32, 44, 62] The well index of the standard model was thus kept at WI = 1.0 to offer sufficient light to all adjacent spaces, regardless of orientation.

Reflectance values of surfaces were set to the maximum values recommended in the Swedish version of the European standard EN 12464-1 (see table 1.2), i.e. ceilings = 0.9, walls = 0.8, and floors = 0.5. [36] Specularity and roughness of opaque materials was set to zero so that these surfaces were perfectly diffuse and would reflect light equally in all directions. [22]

The plan depth was set to a value which resulted in no or negligible contribution from the back wall of the test zones. Preliminary simulations showed that with the slab depth set to 10 m the light either reflected very little or not at all of the back test zone of each floor. This plan depth was thus kept in order to avoid increasing calculation time. [22]

Similar to the plan depth, the appropriate number of floors for the base model was chosen to give a noticeable change in daylight distribution between floors without generating to many simulation points.[23] Cole, Ashehoug and Calcagni all performed their simulations on five storey building models. Furthermore, in preliminary simulations made by the author, a five storey building was found to give a good representation of daylight distribution on different building levels, without generating to much simulation time, hence a total of five storeys was chosen for the base model.

It was decided to use a roof structure in stead of having the atrium open towards the sky because that might result in highly optimistic results. A flat glazed roof structure was used for the atrium top as it was thought to be the most neutral roof type.

[21]The well index is explained in section 2.7

[22]Increasing the plan depth would have resulted in a larger test surface, thus creating more simulation points on the analysis plane and increasing calculation time.

[23]Increasing the number of floors would have resulted in a great increase in simulation points, thus increasing the simulation time.

2.3 Assumptions

- All floor plans were assumed to have no internal obstructions such as walls, furniture, occupants, etc.
- Simulations were performed with annual climate data from the Stockholm, Sweden.
- No external obstructions (trees, buildings, landscape, etc.).
- The atrium roof was modelled without structural elements or other protrusions that might block the sun.
- Light transmittance of all glazing elements were set to 70% for adequate daylight transmittance.

2.4 Work process

The work process, illustrated in figure 2.3, generally consisted of four main steps which were repeated for each simulation:

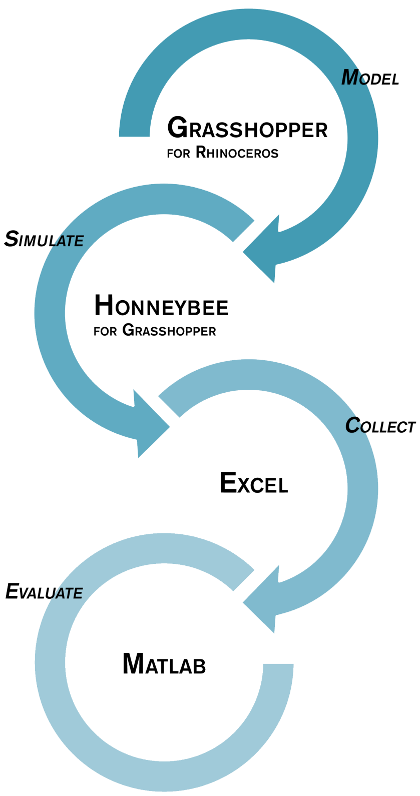


Figure 2.3: A diagram showing the work process of the simulations.

Model: A model was created where selected parameters were chosen to be altered in the simulation Each model was based on the standard model.

Simulate: A dynamic daylight simulation was carried out to test the effect of chosen parameters. Simulations were carried out on a personal desk computer, except for a few simulations which were made on an external in-house super computer at White Arkitekter.

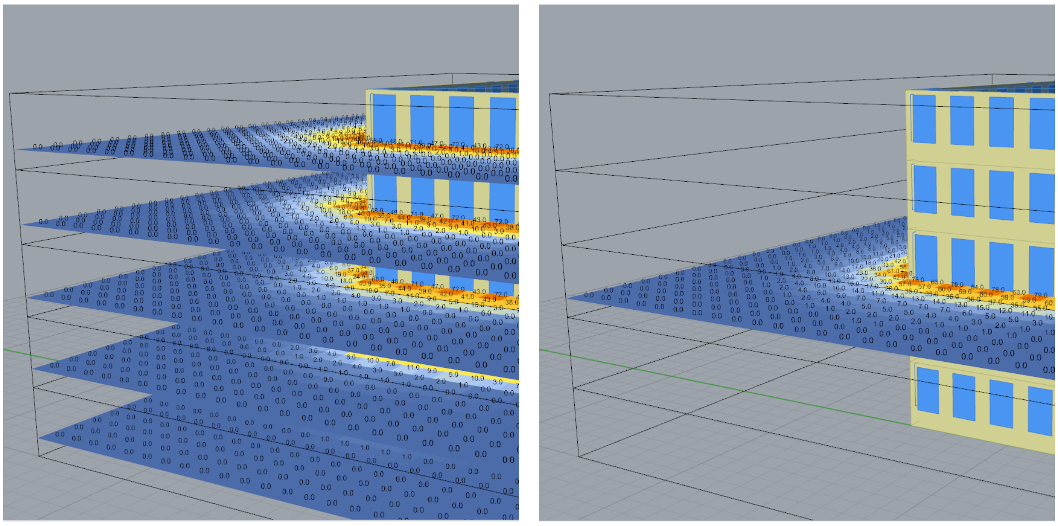
Collect: The simulation results were collected for evaluation. Screen-shots were taken of the gradient colour mesh of three floors (top, middle, and bottom) to be compared for each increment of the chosen parameter of each study. Numeric data of the daylight autonomy in selected points was gathered into Microsoft Excel for further evaluation.

Evaluate: Evaluation was made of the daylight autonomy from the selected points in the previous step, by scripting and plotting in Matlab.

2.5 Data collection & representation

Result data is given at sensor points which are defined on an analysis grid at a user-defined distance (here chosen as 0.8 m) above the floor of each building level. The results contained either daylight factor values for static simulations, or daylight autonomy for dynamic simulations. The grid-size of the analysis grid determines how many sensor points are used in the simulation. It was therefore decided to set the grid-size to $1\,\mathrm{m} \times 1\,\mathrm{m}$, in order to obtain relatively fine results without having to perform immensely long simulations.[24] It is important to keep in mind that a finer grid will increase the calculation time, especially in large scale models, as was the case in this thesis.

Honeybee stores the simulation results in csv-files, which allows the user to easily access the results. How the results are displayed, visually or numerically, is therefore entirely up to the user. Components, provided in Grasshopper, as well as from Honeybee example files, were used to visualize the results on a gradient colour mesh as illustrated in figure 2.4a. An algorithm was created to separate the numerical and graphical results of each floor plan, so that the numeric data and graphical interpretation could be viewed separately for each floor plan respectively, as shown in figure 2.4b.



(a) Results displayed on every floor plan simultaneously

(b) Results displayed separately for a single floor plan

Figure 2.4: Results viewed on all floor plans (left) and on a single floor plan (right).

[24]It should be noted that even with the chosen grid-size, each simulation took up to 17 hours.

Results were compared in sensor points, spaced 1.0 m apart, along a center line reaching from the atrium wall to the façade wall as shown in figure 2.5. In order to achieve this, an algorithm had to be made to collect the results from the points of interest. The algorithm allowed to quickly gather results from relevant sensor points, from all floors into an Excel-file, by click of a button. The Excel-file was next used together with MATLAB to plot and evaluate the results from the selected points.

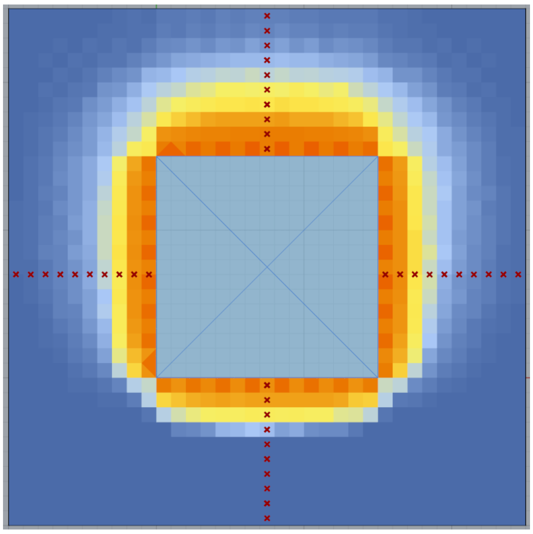


Figure 2.5: Results were compared in sensor points along a center-line reaching from the atrium wall to the façade wall.

The resulting daylight autonomy from the simulations was thus evaluated in two formats, by observation of the color-mesh generated with Honeybee and Grasshopper components, and graphically by evaluating plots generated in MATLAB. By doing this, the benefits of the atrium (with regard to the parameters being evaluated) could be compared between floors as a function of distance from the atrium façade.

2.6 Hypothesis

Given that the object being studied is a complex building object, which has many functions that can have influence on the desired outcome, the author believes that more than one hypothesis needs to be tested to reach a satisfactory outcome. To study the atria in terms of optimisation of daylighting, multiple study-questions, presented in appendix B, are formulated with regard to the design of various aspects within the atrium and the resulting daylight autonomy within the building floor plans. A null hypothesis thus applies for the relevant study questions:

$H_0 \rightarrow$ *The design of an atrium can be optimized for daylight autonomy on all floors of a building (with regard to the parameter in question).*

Hence, the opposing hypothesis is formulated as follows:

$H_1 \rightarrow$ *The design of an atrium can* ***not*** *be optimized for daylight autonomy on all floors of a building (with regard to the parameter in question).*

2.7 Atrium geometry

The well index (WI) is a way to describe the geometry of atria with a number. The well index, which expresses the relationship between the light-admitting area, i.e. the area that is open to the sky, and the surfaces of the atrium well, can be defined with the height (H), width (W), and length (L) of the atrium [9, 21, 62]:

$$\mathrm{WI} = \frac{\mathrm{H} \times (\mathrm{W} + \mathrm{L})}{2 \times \mathrm{W} \times \mathrm{L}} \tag{2.2}$$

A higher well index means the atrium space is deep and narrow, resulting in low levels of daylight at the base of the atrium. A low well index on the other hand indicates that the atrium is shallow and wide in proportion to its height, which in turn offers more light in the atrium and its adjoining spaces. [62]

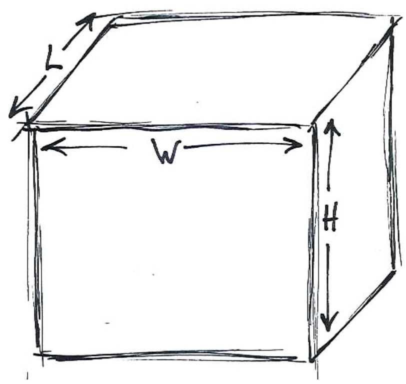


Figure 2.6: Dimensions of the atrium well [21]

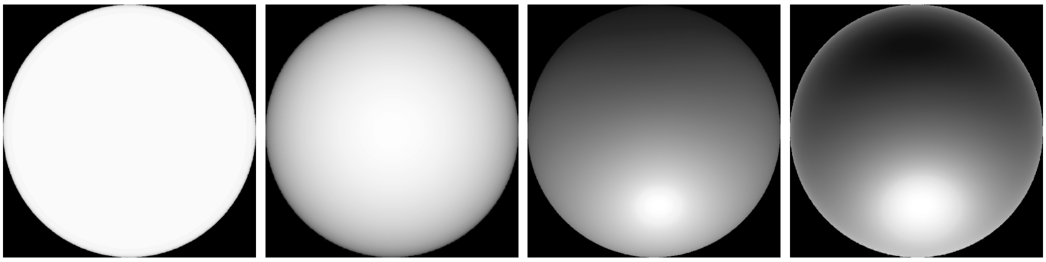
Other indicators for describing atrium geometry exist, such as the plan aspect ratio (PAR) and the section aspect ratio (SAR). The SAR is defined as the height-to-width ratio, while the PAR is defined as the width-to-length ratio. The well index can be written in terms of the SAR and PAR:

$$\mathrm{WI} = \frac{\mathrm{H} \times (\mathrm{W} + \mathrm{L})}{2 \times \mathrm{W} \times \mathrm{L}} = \frac{1}{2}\frac{\mathrm{H}}{\mathrm{W}}\left(1 + \frac{\mathrm{W}}{\mathrm{L}}\right) = 0.5\mathrm{SAR}\,(1 + \mathrm{PAR}) \tag{2.3}$$

Due to the fact that the well index combines the two aspect ratios, the WI is the geometric indicator most commonly used. [1, 32, 62]

2.8 Sky types

The daylight which a building receives originates from the sky, either as direct daylight from the sun or diffuse daylight from the earth's atmosphere. The light which a building receives thus relies on the sky condition which is characterized through the luminous distribution of the hemisphere. *"This physical quantity is usually presented by a two dimensional function which yields luminance values in different sky directions."* [56]



(a) Uniform Sky **(b)** Standard Overcast Sky **(c)** Intermediate Sky **(d)** Clear Sky

Figure 2.7: The CIE sky types are categorized into groups of overcast, intermediate and clear sky conditions. Explanation of the uniform sky is given in the descriptions below. The above sky types are simulated in Honeybee through RADIANCE.

In an article by Darula and Kittler, related to the proposed draft of the International Commission on Illumination[25] standard *ISO 15469:2004 Spatial distribution of daylight*, fifteen sky types are defined based on the description of luminance distribution of the skies. The categorisation of the skies is the result of work made by Nakamura et al., which classified skies into three groups of overcast, clear and intermediate, and the further categorisation made by Kittler et al. of sky types into groups of five overcast, five clear and five translational skies. Calculation of the relative luminance distribution of sky types are defined by parameters describing atmospheric conditions and the position of the sun. [17]

The chosen sky model for a given calculation depends on the type of daylight simulation being implemented. For static simulations made with RADIANCE, either of the two extreme CIE sky types, i.e. totally overcast or perfectly clear sky (figures 2.7b and 2.7d), are most likely used. These are normative sky types, and although the clear sky varies with geographic location and time, simulations made with these sky models are only made for a single point in time. For annual performance, all sky models must be included in the simulation, which is what DAYSIM brings to the table. DAYSIM uses EnergyPlus climate files for specific geographic locations to automatically model all sky conditions of the year. [56]

[25] Commission Internationale de l'Éclarage (CIE)

The main simulations of this thesis were done under a wide range of occurring skies associated with the annual weather profile for the chosen location[26], except for the static simulations where the CIE standard overcast sky was used. To give a notion of the difference between sky types, a short description is given on the main sky models:

Clear sky: Defined as a sky with 0–30% cloud cover. Clear skies generally have higher radiation than other skies, and are generally brighter, i.e. have high luminance and therefore create stronger shadows than other skies. The sky is brightest nearest the sun, and away from the sun it is about three times brighter at the horizon than at the zenith[27]. The CIE standard clear sky has 0% cloud cover. [8, 47]

Overcast sky: A sky that has 70–100% cloud cover. Overcast skies generally have lower luminance, lower radiation, and create weak shadows and more diffuse lighting, relative to more clear conditions. The sky is about three times brighter at the zenith than at the horizon. The CIE standard overcast sky is 100% covered in clouds. [8, 47]

Intermediate sky: This sky type varies from mostly cloudy with clear patches, to mostly clear with few clouds, and is therefore very difficult to predict. The sky condition is defined as a sky with 30–70% cloud cover, and is the condition between overcast and clear sky. [8, 47]

Uniform sky: This standard sky type is a remains from the days when calculations were done by hand or with tables. The sky is characterised by a uniform luminance that does not change with altitude or azimuth. [3] This sky is generally listed as the 16$^{\text{th}}$ CIE sky type and is seldom used due to its uniform luminance distribution.

[26] Geographic location of climate file: Stockholm, Sweden

[27] The *zenith* is defined as the top of the sky dome. A point directly overhead, 90° in altitude angle above the horizon. [8]

2.9 The Daylight factor method

The *daylight factor* (DF) method is a form of static daylight performance metrics. The method was developed early in the 20th century in the United Kingdom, and is today one of the most widely used daylight metrics. The daylight factor is the ratio which represents the amount of illuminance available indoors on a horizontal plane, relative to the illuminance present outdoors at the same time under an unobstructed CIE standard overcast sky. [35]

The daylight factor is given as a percentage, and can be expressed with the following equation:

$$\mathrm{DF} = \frac{\mathrm{E_I}}{\mathrm{E_O}} \times 100 \qquad [\%] \tag{2.4}$$

where
$\mathrm{E_I}$ is the illuminance at a point in the interior of the room being analysed
$\mathrm{E_O}$ is the illuminance from the unobstructed sky on a horizontal surface outside

Another way of calculating the daylight factor is outlined by Löfberg [41] with the sum of three components, each as a percentage of the exterior unobstructed illuminance received at the interior reference point:

- Sky component (SC) – directly from the sky through a glazed surface (i.e. window or sky light)

- Externally reflected component (ERC) – from reflecting exterior surfaces above the horizon

- Internally reflected component (IRC) – from all light reflected from the interior surfaces of a space

The daylight factor thus becomes

$$\mathrm{DF} = \mathrm{SC} + \mathrm{ERC} + \mathrm{IRC} \tag{2.5}$$

Methods of calculating the three aforementioned components are outlined in detail in Löfbergs book, *Räkna med Dagsljus*, and will not be explained in more detail here since, in this thesis, the evaluation of the daylight factor was made with computer simulation programs (see sections 2.12 and 2.13). It is however worth mentioning that the daylight factor presented with equation 2.5 should be multiplied by several correction factors to obtain the correct value. These correction factors include the dirt factor, the glazing transmission factor and factors for window frame and glazing bars, see Löfberg's book for further detail.

2.10 Limitations of the daylight factor method

Even though the daylight factor is widely used and quite simple and quick to evaluate, it is a *static daylight performance metric* with much constraint. The term static daylight performance metric means that the method of measurement is taken at a single point in time for one single sky condition (generally the CIE Standard Overcast Sky or the CIE Standard Clear Sky). This clearly introduces some limitations to the method. For instance, design recommendations based on the daylight factor are the same for all façade orientations and building locations. [28] *"Another shortcoming of the daylight factor approach is that the underlying CIE overcast sky tends to underestimate luminances near the horizon. As a consequence, illuminances in sidelit/toplit spaces are usually under/over predicted."* [56] Daylight factor outputs are however helpful in making quick comparison of relative daylight penetration under overcast sky condition and it is the most common metric used when studying physical models. [35]

Due to its simplicity and fairly quick calculation time, the daylight factor method was used in the assessment of daylight simulation software presented in appendix A. The use of dynamic daylight metrics was however used in the main simulation process.

2.11 Dynamic daylight metrics

Dynamic daylight performance metrics are based on time series of illuminances or luminances within a building. These time series usually extend over the whole calendar year and are based on external, annual solar radiation data for the building site. *"The key advantage of dynamic daylight performance metrics compared to static metrics is that they consider the quality and character of daily and seasonal variations of daylight for a given building site together with irregular meteorological events."* [28]

It is believed that the static approach of daylight simulation is not sufficient in advanced daylight design in architecture due to the dynamic seasonal performance of buildings. In the research associated with the simulations of this thesis, one dynamic daylight metric in particular, *daylight autonomy*, was therefore used for evaluating performance of the atria models.

2.11.1 Daylight autonomy

Daylight autonomy (DA) is a simulation method which evaluates the daylight quantity associated with any given hour, geographic location, and sky condition on an annual basis. Daylight autonomy was the first of a string of annual daylight metrics, now commonly referred to as *dynamic daylight metrics*. It is presented as a percentage of annual daytime hours that a given point in a space is above a specified illumination level. [35] Furthermore, daylight autonomy uses work plane illuminance as an indicator of whether there is sufficient daylight in a space so that occupants can work by daylight alone. [28] Thresholds for work plane illuminance values are given in certification documents such as LEED, where the minimum value is 300 lux, or as recommended in table 1.1. In this thesis the daylight autonomy threshold was chosen as 300 lux to represent the requirement of the LEED certification system.

2.11.2 Alternative dynamic daylight metrics

Recently, modified methods of daylight autonomy have been introduced, such as continuous daylight autonomy, useful daylight illuminance, and spatial daylight autonomy. In *continuous daylight autonomy* (cDA), introduced by Rogers and Goldman in 2006 [58], partial credit is attributed to time steps when daylight illuminance lies below the minimum illuminance level. For example, when a point receives 400 lux but the required illuminance is 500 lux, the point is credited 400/500 or 80% for that time step. *"This method gives credit to spaces that are not fully saturated with daylight, but do receive some daylight contribution."* [58] *Useful daylight illuminance* (UDI), proposed by Mardaljevic and Nabil in 2005, aims to determine when daylight levels are useful for the occupants, i.e. neither too dark nor too bright. The threshold proposed by Mardaljevec and Nabil is 100 lux for the lower limit and 2,000 lux for the upper limit, where the upper limit might lead to discomfort such as glare or thermal. *"There is however significant debate regarding the selection of 2,000 lux as an 'upper threshold' above which daylight is not wanted due to potential glare or overheating. There is little research to support the selection of 2,000 lux as an absolute upper threshold."* [28, 35] *Spatial daylight autonomy* (sDA) is the percentage of area that is above 300 lux 50% of the time or more during annual occupancy hours for a certain percentage of floor area. Additionally, a metric called *annual sunlight exposure* (ASE) can be used to evaluate the occurrence of direct daylight (> 1000 lux) on annual basis. The metric sets a threshold on the percentage of area (defined as 10% in LEED) that is allowed to receive direct daylight for more than 250 hours per year. [16, 55]

Daylight autonomy was chosen as the measurement parameter in this thesis as it was thought to be the most appropriate of the aforementioned dynamic parameters. ASE is more relevant to glare studies, and cDA and UDI are only recently modified and non-validated versions of daylight autonomy. Furthermore sDA is meant to give an evaluation of the daylight over the whole floor area while DA gives us the opportunity to evaluate the daylight in every point over the floor, which is ultimately why it was deemed most fit for this study.

2.12 Dynamic daylight simulations

Dynamic daylight simulations (DDS) require a three dimensional computer generated model of a building which contains information on the geometry of the building and its surroundings as well as reflection and transmission characteristics of material surfaces. [56] The dynamic simulation capabilities of Honeybee are directly coupled with the RADIANCE and DAYSIM simulation engines so that both the 3D modelling of the building and the daylight simulation can be done within the same interface, as previously stated. DAYSIM uses a *daylight coefficient approach* together with the RADIANCE algorithm to evaluate annual illuminance profiles. For dynamic daylight simulation in DAYSIM, an annual climate file[28], which includes hourly data of direct and diffuse irradiances for the building's location, has to be imported into the building model. In the method, a horizontal work plane is chosen at a specific distance above the floor. For the purpose of this thesis, the work plane height was set to a standard height of 0.8 m in accordance to Miljöbyggnad. The work plane is next split into a grid of sensor points in which the calculations take place, as was explained in section 2.5. The ray-tracing algorithm of RADIANCE is then used to evaluate the daylight in the sensor points. The simulations involve a pre-processing step during which a set of daylight coefficients is calculated for each sensor point and a post processing step during which daylight coefficients are coupled with the climate data to yield the annual time series of interior illuminances and luminances. [28]

The method utilises a sky-subdivision model proposed by Treqenza in 1989 in which the hemisphere is divided into 145 segments of roughly equal size. After the sky division a daylight coefficient is calculated for each sensor point x relating to a sky segment, S_α, with the equation:

$$\mathrm{DC}_\alpha(\mathrm{x}) = \frac{\mathrm{E}_\alpha(\mathrm{x})}{\mathrm{L}_\alpha \cdot \Delta\mathrm{S}_\alpha} \tag{2.6}$$

where E_α is the illuminance in point, x, L_α is the luminance defined in the weather-file at the center of the sky-patch, and $\Delta\mathrm{S}_\alpha$ is the angular size of the sky patch S_α. The angular size of an object refers to the size of the object at a distance as seen from a point at a specific angle, defined as

$$\Delta\mathrm{S}_\alpha = 2\arctan\left(\frac{\mathrm{S}_\alpha}{2\mathrm{d}}\right) \tag{2.7}$$

where d is the the actual distance to the object. Contributions from the ground are calculated in the same way, but by dividing the ground plane into 3 segments. Similarly, contributions from direct sun are accounted for by defining 48–65 representative sun positions depending in site latitude. The total illuminance in a sensor point is then obtained by summing the contribution from sky, ground and sun:

[28] Weather data for more than 2100 locations is available for download in EnergyPlus weather format (.EPW) on the US Departmend of Energy website.

$$E(x) = \underbrace{\sum_{\alpha=1}^{145} DC_{\alpha}^{sky} \cdot L_{\alpha}^{sky} \cdot \Delta S_{\alpha}^{sky}}_{\text{diffuse sky}} + \underbrace{\sum_{\alpha=1}^{3} DC_{\alpha}^{ground} \cdot L_{\alpha}^{ground} \cdot \Delta S_{\alpha}^{ground}}_{\text{ground reflection}} + \ldots$$

$$\ldots + \underbrace{\sum_{\alpha=1}^{N} DC_{\alpha}^{sun} \cdot L_{\alpha}^{sun} \cdot \Delta S_{\alpha}^{sun}}_{\text{direct sun}} \tag{2.8}$$

Contribution from each segment is traced from the sensor point and back to the segment using the backward ray-tracing algorithm of the RADIANCE software. [56]

2.13 Backward ray-tracing

In the backward ray-tracing algorithm, light is traced from the viewpoint and up to specific points in the hemisphere. The algorithm takes into account all physical interactions with the surfaces of the objects composing the scene. These objects are described using a Cartesian coordinate system where the x-axis is directed towards the East, the y-axis towards the North and the z-axis towards the zenith. [13]

Each light ray carries a certain amount of radiance[29], which in RADIANCE is expressed in terms of the colour each light ray carries. The radiance is thus divided into three channels corresponding to red (r), green (g) and blue (b) primary colours, known as RGB-channels. The ray-tracing algorithm in RADIANCE uses the weighted sum of the RGB-channels to interpret the radiance in every single point with the following equation:

$$\mathrm{R} = 0.265 \cdot \mathrm{r_r} + 0.670 \cdot \mathrm{r_g} + 0.065 \cdot \mathrm{r_b} \qquad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] \tag{2.9}$$

To obtain the illuminance, E, in a point, equation 2.9 is multiplied by a factor that accounts for the luminous efficacy[30], $\mathrm{R_{eff}}$, of the sky. For standard skies in RADIANCE the luminous efficacy is 179 lm/W. The illuminance can thus be written as

$$\mathrm{E} = \mathrm{R_{eff}} \times (0.265 \cdot \mathrm{r_r} + 0.670 \cdot \mathrm{r_g} + 0.065 \cdot \mathrm{r_b}) \qquad \left[\frac{\mathrm{lm}}{\mathrm{m}^2}\right] \tag{2.10}$$

In order to obtain the daylight factor in a point, equation 2.10 is divided by the illuminance value at the zenith of the CIE standard overcast sky, 10,000 lux, and multiplied by 100 to get a percentage value. Thus obtaining:

$$\mathrm{DF_{RAD}} = \frac{179}{10,000} \times (0.265 \cdot \mathrm{r_r} + 0.670 \cdot \mathrm{r_g} + 0.065 \cdot \mathrm{r_b}) \times 100 \tag{2.11}$$

[29] Note that here 'radiance' refers to the radiant intensity of light on a surface, while RADIANCE refers to the name of the light simulation software.

[30] *Luminous efficacy* is the effectiveness of illumination, i.e. how well a light source produces light [42]

The calculation carried out in RADIANCE can be divided into three main parts:

- the *direct component*, consisting of light arriving at a surface directly from light sources,
- the *specular indirect component*, consisting of light arriving at a surface from other surfaces and being reflected off or transmitted through a directional manner, and
- the *diffuse indirect component*, consisting of light arriving at a surface and being reflected or transmitted with no directional preference. [10, 39]

This method of calculation is exactly as explained in the daylight factor method with equation 2.5. The quantity and quality of these components are evaluated in the ray-tracing algorithm and the Monte Carlo method through defining a set of RADIANCE-parameters which ultimately determine the quality of the simulation results.

The difficulty of using RADIANCE is that the program is very complex to learn, and many adjustable parameters have to be properly set to achieve a good result within a reasonable amount of time[31]. This can be quite cumbersome for the inexperienced user. [13, 56] Honeybee adapts RADIANCE to common users and allows the user to manipulate five of these parameters, i.e. number of ambient bounces, divisions, super-samples, resolution, and accuracy. Altering these parameters can result in increased simulation time, as is explained in table 2.1. Values should therefore be chosen in accordance to the level of detail that is needed for a particular model.

Table 2.1: Effect on execution time associated with RADIANCE-parameters [39]

Parameter	Effect on execution time
-ab	doubling this value can double rendering time
-aa	doubling this value approximately quadruples rendering time
-ar	effect depends on scene, can quadruple time for double value
-ad	doubling value may double rendering time
-as	effectively adds to -ad parameter and its cost

Table 2.2 gives an example of how the RADIANCE-parameters can be defined in order to achieve a certain level of detail. The highest quality setting provided in Honeybee was chosen for the simulations in this study. It should be noted that individual parameters could be set to higher values if the user desired to do so, although that would significantly increase simulation time as explained in the above table.

[31] A complete list of ray-tracing RADIANCE parameters with detailed description is given on http://radsite.lbl.gov/radiance/man_html/rtrace.1.html

Table 2.2: RADIANCE-parameters and the quality of daylight simulation as defined in the Honeybee software. Depending on the level of detail desired, specific values are chosen for ambient bounces (-ab), ambient divisions (-ad),ambient super-samples (-as), ambient resolution (-ar), and ambient accuracy (-aa).

	RADIANCE - parameters				
Simulation quality	*-ab*	*-ad*	*-as*	*-ar*	*-aa*
Low quality (initial simulation)	2	512	128	16	0.25
Medium quality	3	2048	2048	64	0.20
High quality (final simulation)	6	4096	4096	128	0.10

The only light source in the simulation is the sky, which means that how the light travels within the building model mostly depends on the parameters that control the indirect component in the calculation. In other words, adjusting parameters which control the direct component will have far less effect than the parameters that control the indirect component. The calculation parameters most crucial to the simulation are therefore the ones that decide how the light reflects within the building model, i.e. the parameters defined in tables 2.1 and 2.2.

Dubois (2001) observed in a sensitivity analysis of RADIANCE parameters that increasing the accuracy of indirect diffuse options had much more affect than altering the direct options. Furthermore, she noticed that little or no difference in results was observed close to the windows, but a great difference could be seen further into the model, thus backing the aforementioned importance of choosing the appropriate ambient options (indirect diffuse). The reason that little change was noticed close to the window is that in that region the analysis plane receives direct light, while further away from the window it is mostly indirect light that reaches the analysis plane. [22]

In the following text a description of the RADIANCE parameters directly available to the user within the Honeybee interface is given[32]:

Ambient bounces

The *number of ambient bounces* (-ab) is the parameter that controls the maximum number of diffuse bounces in the indirect calculation. The value of -ab should generally represent the number of reflections required for a light to reach the point of interest. Setting the value of ambient bounces to zero, means that ambient calculations are switched off. With ambient calculations switched off, direct light will reach a the point of interest if possible, but the contribution of the direct light into the room will not be considered. [22, 43]

[32]Note that Honeybee automatically sets values for the direct component and the specular indirect component. For more information on these components, please refer to the link mentioned in footnote 31.

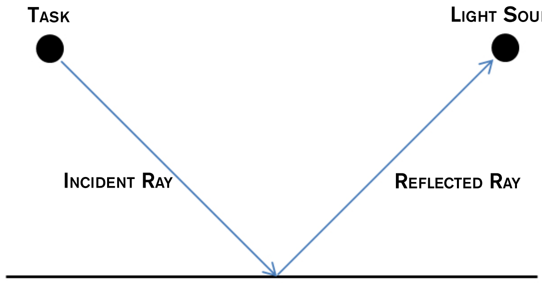


Figure 2.8: Number of ambient bounces is set to the number of reflected rays needed to reach a light source. The image shows how the light is traced back to the source from the task. [52]

Ambient divisions

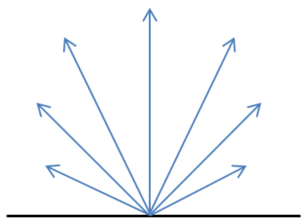


Figure 2.9: Number of ambient divisions sets the number of sampling rays sent from each point into the hemisphere.

Ambient divisions (-ad) is the parameter that controls the number of sampling rays sent from each point into the hemisphere. Consequently, a value of zero implies no indirect calculation. Increasing this parameter, as well as the value for ambient super-samples, increases the accuracy of the simulation. [22, 43]

Ambient super-samples

The *ambient super samples* (-as), which is generally set to about ad/2 or ad/4, is the number of extra rays used to sample areas in the hemisphere with high variability. Super sampling improves accuracy of scenes with large bright and dark regions by carefully sampling shadow boundaries. [22, 43]

Ambient accuracy

The *ambient accuracy* (-aa) sets the maximum error permitted in the indirect irradiance interpolation. Normally, values between 1 and 0.1 are used, with lower values giving the best accuracy. Setting the value to zero will result in no interpolations. [43]

Ambient resolution

The ambient resolution (-ar) sets the distance, S, between ambient calculations by determining the maximum density of ambient values used in interpolation. The accuracy of the indirect calculation will start to relax at distances less than the maximum scene size divided by this number. This setting avoids to overloading the program with unimportant geometric details (small objects). [13, 22, 43]

Chapter 3: Results & discussion

In the following sections, results from the various simulations are presented along with a short discussion on each simulation. The results and evaluations consist of the information included in the guideline document. A study question, relating to each individual simulation, is therefore presented at the start of each section. Each section includes images of the most relevant results, while a complete collection of the results are presented in appendix C.

3.1 Atrium shape

Study question: *How does the base-shape of the atrium (i.e. square, triangular, circular) affect the daylight distribution?*

Changing the shape of an atrium will affect how the light is reflected within the atrium. The intention with this simulation was to see which shape resulted in the most uniform daylight autonomy in the adjacent spaces of the atrium. Three basic geometric shapes were thus compared, i.e. square, circular and two orientations of a triangular shape. Comparing the simulation results from the three shapes is quite difficult due to the fact that the glazing distribution and orientation will vary depending on the shape. The area of the atrium walls will also depend on the shape. The volume of the atrium was therefore kept constant for this simulation and a comparison was made graphically between the bottom-, middle-, and top-floor of each shape, respectively. The models were constructed in such a way that the minimum distance from atrium to façade was ten meters. This was done to ensure that the light would not be reflected back of the façade walls.

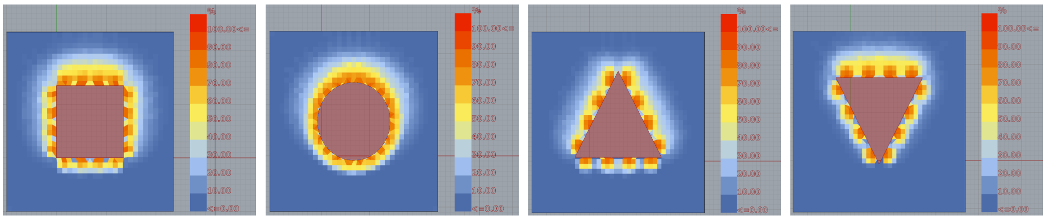


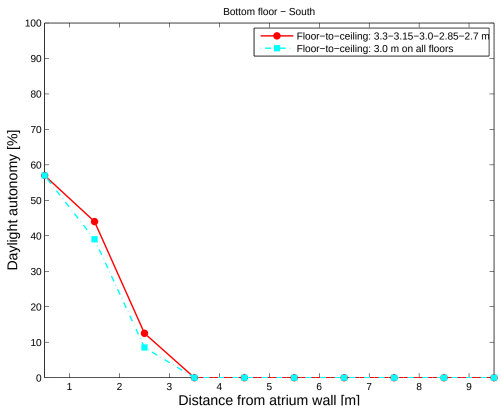
Figure 3.1: Daylight autonomy distribution compared between 4 different atrium shapes

Apart from the corner regions of the square shape, the circular shape offers quite similar distribution of daylight autonomy to the square shape. The triangular shape is the least favourable of the three shapes. The zones which receive no light from the atrium are the largest for this shape, which means that more artificial lighting will be needed in these zones. Of the two triangle shape orientations, the north pointing triangle (second from the right in figure 3.1) is perhaps the better of the two since more light is distributed to the sides of the floor plan. The overall area which does not receive light from the atrium is thus smaller for this orientation. It can however be argued that the atrium shape should reflect the overall building shape, meaning that if the building is in the shape of a triangle then the atrium should be in the shape of a triangle as well. This will ensure that light is distributed evenly within the building. Figure 3.1 shows the daylight autonomy distribution on the top floor of the building model. The distribution on the bottom and middle floor can be seen in appendix C.1.

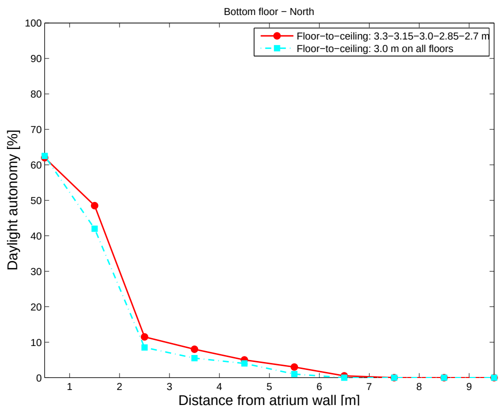
3.2 Floor-to-ceiling height

Stidy question: *Can floor-to-ceiling heights within a building be varied to increase daylight autonomy on lower floors?*

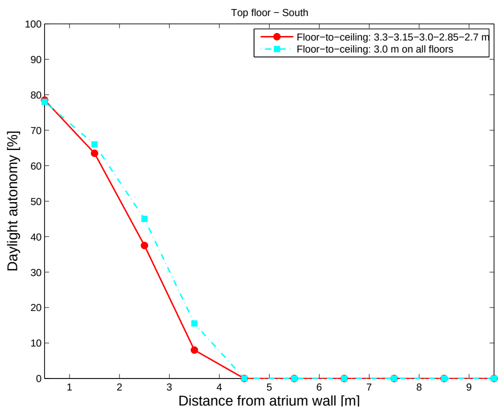
The floor-to-ceiling height was varied by 0.15 m between floors in the test building so that the bottom floor was 3.3 m high and the top floor was 2.7 m. This solution was then compared to the standard building which had a floor height of 3.0 m on all floors. The overall height of both buildings thus being 15 m.



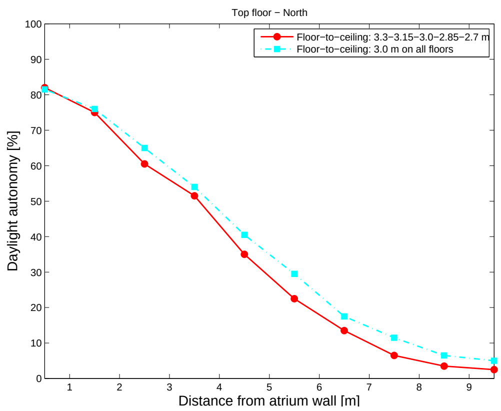
(a) Bottom floor – South slab



(b) Bottom floor – North slab



(c) Top floor – South slab



(d) Top floor – North slab

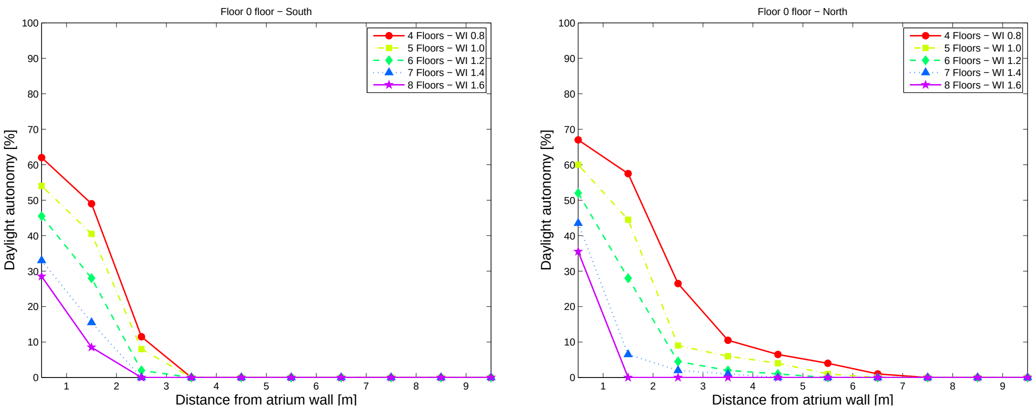
Figure 3.2: Daylight autonomy for different floor-to-ceiling heights.

Indeed the daylight autonomy increases slightly on the lower floors with increased floor-to-ceiling height, but the opposite occurs on the upper floors as seen in the results in figure 3.2 appendix C.2. On the upper floors the standard building has greater floor-to-ceiling height than the comparison building which has varying floor heights. The simulation therefore shows that increasing floor to ceiling heights will result in increased daylight autonomy in the test points studied.

3.3 Number of floors

Study question: *How high can a building theoretically be for an atrium to have any effect?*

Increasing the number of floors of a building also means making the atrium narrower in relation to its height, unless the well index is kept constant. That is, if the base-area of the atrium is kept the same and the number of floors increased, the atrium will become increasingly narrower in relation to its height with added number of floors. A narrower atrium means that less light is available to the lower floors. It is therefore easy to see that without keeping the WI constant (i.e. increasing the width and length of the atrium with respect to its height and thus increasing the base-area)[33], the daylight autonomy at the lower levels of the building will decrease significantly. The purpose of this simulation is therefore to study for which number of floors, and consequently at which well index, the daylight autonomy becomes very poor at the lower levels. The simulation parameter for this study question thus consisted of simulating the daylight autonomy for a 4, 5, 6, 7 and 8 floor building. Figure 3.3 shows the daylight autonomy along a center line reaching from the atrium wall to the façade at the bottom floor of the North and South slabs, respectively. The compiled results, showing both the plotted results of each floor of interest and the gradient colour mesh of the bottom floor of each building, are given in appendix C.3.



(a) Bottom floor – South slab **(b)** Bottom floor – North slab

Figure 3.3: Daylight autonomy along a center line reaching from the atrium wall to the façade at the bottom floor of the North and South slab, compared with the number of floors.

By increasing the height of the building by one floor at a time the daylight autonomy decreases quite a lot on all floors and orientations studied within the building. For the highest building studied (with 8 floors) the daylight autonomy does not extend past 1.5 m on the bottom floor while the daylight autonomy is still noticeable at 5.5 m for the lowest building (4 floors) on the same floor. If only the point closest to the atrium well is compared 10% difference can be observed between

[33] See section 2.7.

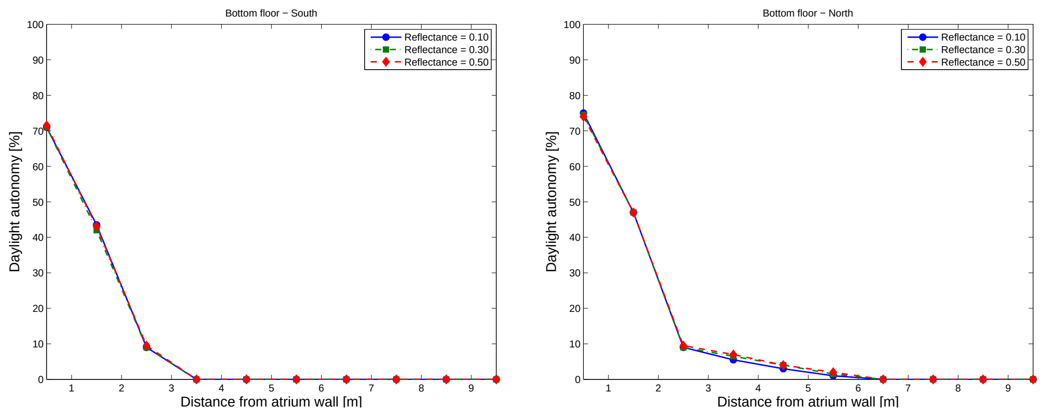
added heights. Not so surprisingly, the daylight autonomy reaches furthest into the floor plan, on all floors studied, for the building with the lowest well index. This is logical since with added number of floors the view of sky from the lower floor plans becomes smaller, hence less direct light reaches the floor plan in question. With added number of floors the lower levels also need to rely on more reflected light to reach the windows. It can thus be concluded that if an atrium is to reach further down into a building the dimensions of the atrium must be increased simultaneously with regard to the atrium width and length in order to maintain good daylight autonomy at lower levels of the building.

3.4 Reflectance of atrium surfaces

Study question: *Is there significant effect on daylight autonomy by increasing the reflectance of atrium walls and floor, and which surface (wall or floor) has a greater impact?*

Daylight autonomy within the building was simulated with reflectance of the atrium floor and walls set to the mininum, average, and maximum recommended reflectance value of the SS-EN 12464-1 standard (see table 1.2).

3.4.1 Atrium floor



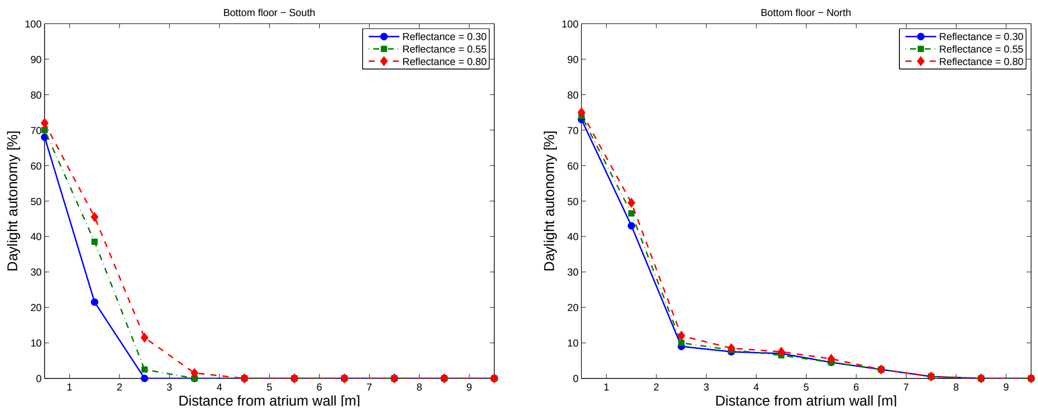
(a) Bottom floor – South slab **(b)** Bottom floor – North slab

Figure 3.4: Daylight autonomy for different atrium floor reflectance

The simulations of this study showed no increase in daylight autonomy within the adjacent spaces of the atrium, as seen on figure 3.4. A reason for this could be that the benefit from increasing the atrium floor reflectance is only noticeable within the atrium itself, and that the benefit is in fact so little that it does not have any impact on the daylight autonomy within the adjacent spaces of the atrium.

3.4.2 Atrium walls

Increasing the reflectance of the atrium walls has a great impact on the South, East and West, orientations of the building, as can be seen in appendix C.4. The increase in daylight autonomy on the North orientation of the building is quite small compared to the other orientations, see figure 3.5. This is because the other orientations receive much more reflected light than the Northern orientation. Within two meters from the atrium window, the daylight autonomy can be increased by up to 30% on the bottom floor of the South orientation, and within three meters the daylight autonomy can go from 0% to 10%.

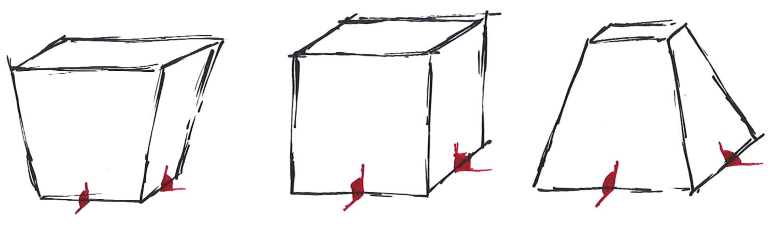


(a) Bottom floor – South slab **(b)** Bottom floor – North slab

Figure 3.5: Daylight autonomy for different atrium wall reflectance

3.5 Atrium slope – A-shape vs. V-shape

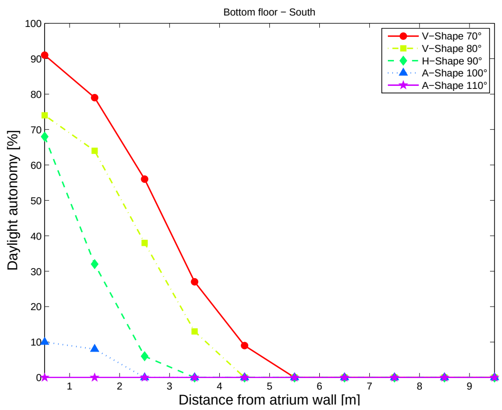
Study question: *How does the slope of the atrium wall effect the daylight distribution and which shape gives the best result?*



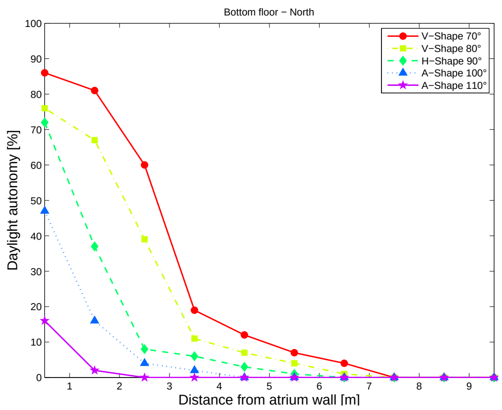
(a) V-shape **(b)** Standard shape **(c)** A-shape

Figure 3.6: A sketch of the three atria shapes studied in this simulation. The walls were angled in $\pm 10°$ and $\pm 20°$ from the standard vertical atrium wall, resulting in a angle of $70°, 80°, 90°, 100°, 110°$ from the horizontal plane, respectively.

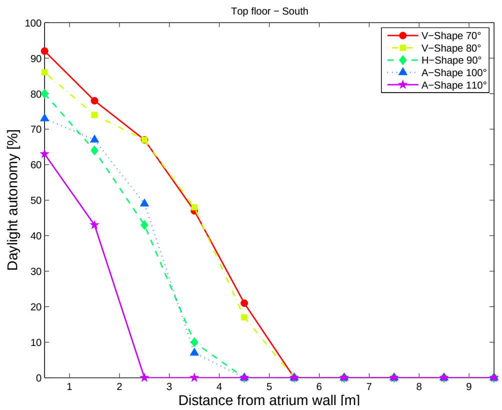
For the purpose of this simulation, all walls were sloped simultaneously so that the atrium was either narrower at the top than at the base, or the opposite. The two variations were then compared to the standard 90° angle atrium. Hence, three shapes were studied, V-shape , H-shape, (standard) and A-shape, as shown in figure 3.6. The atrium volume was kept constant, so that the same amount of exploitable floor area was studied for each shape and wall slope, and the walls were angled in ±10° and ± 20° from the standard vertical atrium wall, resulting in a angle of 70°, 80°, 90°, 100°, 110° from the horizontal plane, respectively.



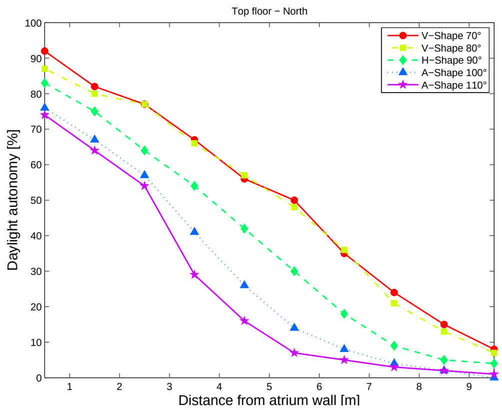
(a) Bottom floor – South



(b) Bottom floor – North



(c) Top floor – South



(d) Top floor – North

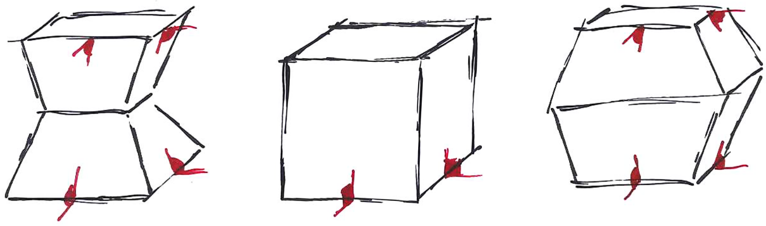
Figure 3.7: Varying the slope of the atrium wall dramatically affects the daylight autonomy within the building.

For all orientations studied, increasing the angle of the walls (thus making the atrium narrower at the top than at the bottom) results in less access to daylight, and consequently less daylight autonomy on the building's floor plans. Little or no decrease in DA occurs for the first 10 degree increase at the upper-most levels, but the DA becomes noticeably poorer at the lower levels. Making the atrium wider at the top than at its base brings a significant increase in DA on all floors as it allows for more access to daylight. Decreasing the angle from 80 to 70 degrees does however only show significant effect on the bottom floors, as seen in figure 3.7 and in appendix C.5.

3.6 Atrium slope – x-shape vs. ◇-shape

Study question: *How does the slope of the atrium wall affect the daylight distribution and what slope gives the best result?*

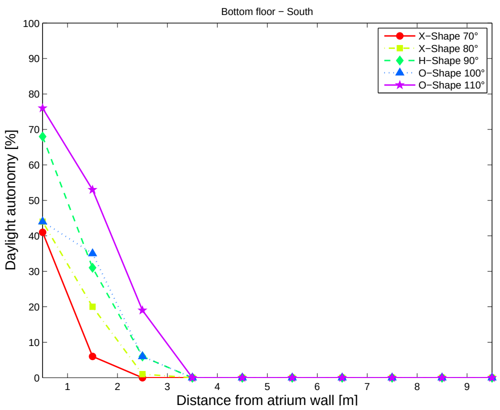
For the purpose of this study, all walls were sloped simultaneously so that the atrium was either narrower at its center than at its top and base, or the opposite, as seen in figure 3.8. The two variations were then compared to the standard 90° angle atrium. Hence, three shapes were studied, x-shape , H-shape, (standard) and ◇-shape. The atrium volume was kept constant so that the same amount of exploitable floor area was studied for each shape and wall slope. The walls were angled, at the top and bottom, in $\pm 10°$ and $\pm 20°$ from the standard vertical atrium wall, resulting in a angle of $70°, 80°, 90°, 100°, 110°$ from the horizontal plane, respectively. One floor was added to the building model for this simulation so that the angled walls would not meet in the middle of a floor, but rather in between floors. Consequently, one floor was also added to the standard model.



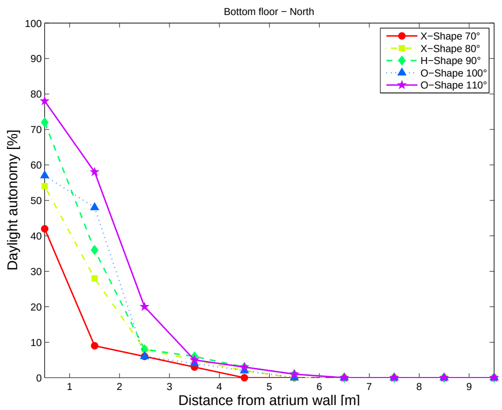
(a) x-shaped **(b)** Standard shape **(c)** ◇-shaped

Figure 3.8: A sketch of the three atria shapes studied in this simulation. The walls were angled, at the top and bottom, in $\pm 10°$ and $\pm 20°$ from the standard vertical atrium wall, resulting in a angle of $70°, 80°, 90°, 100°, 110°$ from the horizontal plane, respectively.

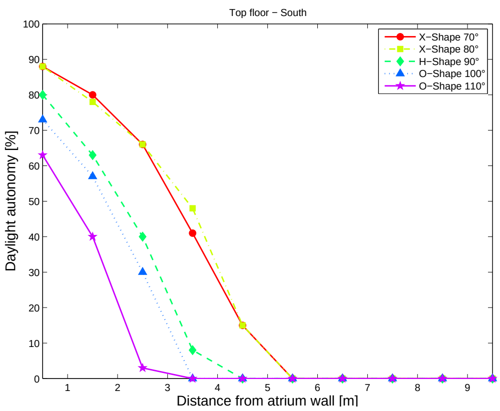
Designing the atrium as suggested above, does not result in better daylight autonomy on all building levels as seen in figure 3.9. The daylight autonomy is noticeably better on those floor plans that have atrium walls leaning back because they have more view of the sky (upper floors in X-shaped atrium and lower floors in ◇-shaped atrium). The floor plans that have atrium walls leaning forward (lower floors in X-shaped atrium and upper floors in ◇-shaped atrium), and consequently no view of the sky, mainly receive reflected light from within the atrium, and therefore have much lower daylight autonomy as seen in appendix C.6 . This is similar to what was shown in the previous study question.



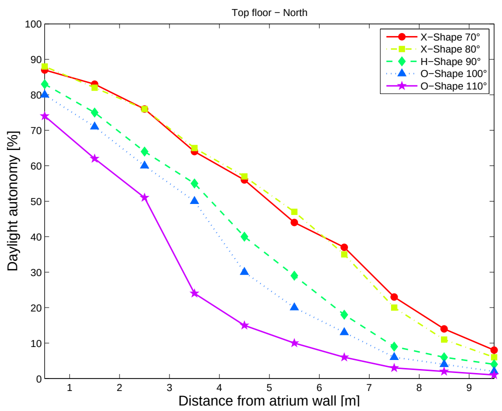
(a) Bottom floor – South



(b) Bottom floor – North



(c) Top floor – South



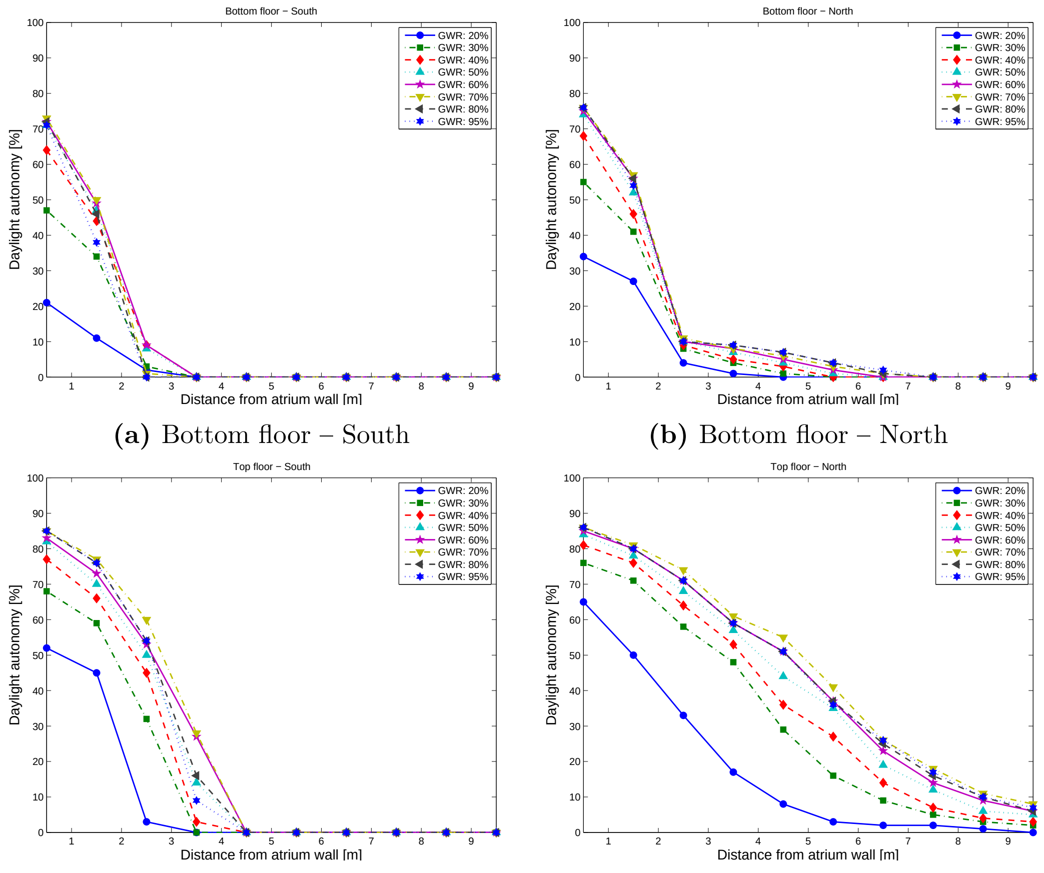
(d) Top floor – North

Figure 3.9: Varying the slope of the atrium wall dramatically affects the daylight autonomy within the building.

3.7 Glazing convergence

Study question: *Is there a certain glazing-to-wall ratio at which increased daylight autonomy can not be noticed if the glazing-to-wall ratio is increased?*

The purpose of this simulation is to see if there is a certain ratio of glazing-to-wall material (GWR) after which the daylight autonomy does not increase. In other words: does the daylight autonomy converge at a certain glazing-to-wall ratio? The glazing-to-wall ratio was increased in increments of 10% and the resulting daylight autonomy studied on the bottom, middle, and top floor, for the South, North, and East orientations, respectively. The simulation program does not allow for glazing ratios higher than 95%, hence GWR=95% was chosen as the highest ratio instead of 100%.



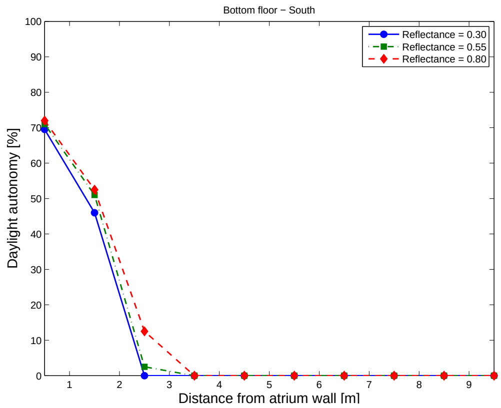
(a) Bottom floor – South **(b)** Bottom floor – North

(c) Top floor – South **(d)** Top floor – North

Figure 3.10: The resulting daylight autonomy for increasing the glazing-to-wall ratio

Daylight autonomy within the analysis plane of each floor studied gradually increases with rising glazing-to-wall ratio, but starts to converge at GWR = 50–60%. Interestingly enough, the highest daylight autonomy is obtained with the

GWR set to 70%. The two higher ratios (80% and 95%) give slightly lower daylight autonomy. An explanation to this could be that with GWR = 70% there is more wall surface present than for the other two ratios, allowing more daylight to be reflected of the walls of the atrium and into the floor plan opposite to the wall of which the light is reflected. With increased GWR the lower levels depend more on direct daylight since the reflective component decreases due to less reflective surfaces within the atrium. In section 3.4, the impact of the reflectance of atrium walls was proven to be quite significant. To evaluate the impact of the reflective component in an atrium with GWR = 70%, the study described in section 3.4 was repeated, but with GWR = 70%.



(a) Bottom floor – South **(b)** Bottom floor – North

Figure 3.11: Even with high GWR the reflectance of atrium walls has an impact.

As seen in figure 3.11 and appendix C.7.1, increasing the reflectance of the atrium walls causes a slight increase in daylight autonomy. The way in which Honeybee generates glazing is also believed to have impact on the difference between GWR = 60% and 70%. With GWR = 70% the glazing is modelled as a single pane, while with GWR = 60% the glazing is split up into several panes, as seen in figure 3.12. As a result, the 70% option has more access to daylight while still providing enough surface for the reflective component to have an impact, which also explains why the daylight autonomy is higher for GWR = 70% than the two higher ratios.

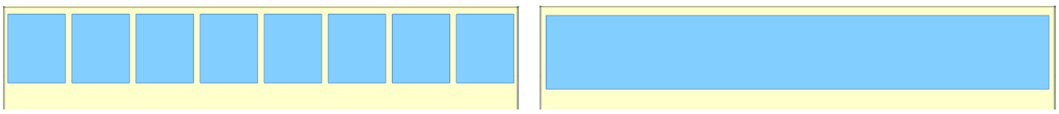


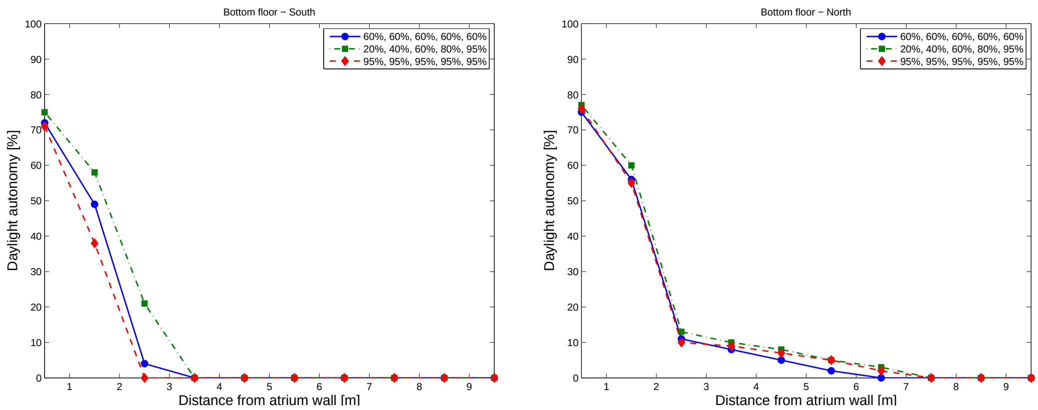
Figure 3.12: GWR = 60% (left) compared to GR = 70% (right).

To evaluate at which GWR the daylight autonomy reaches a maximum and starts to decrease the convergence simulation was run again with GWR = 65% and 75%. The results presented in appendix C.7.2 show that the maximum daylight autonomy is reached at GWR set to 65–75%, after which the daylight autonomy begins to decrease.

3.8 Glazing ratio

Study question: *Does varying the ratio of glazing to opaque material per floor in the atrium well result in a better levels of daylight at lower floors?*

An overall glazing ratio of 60% within the atrium of a 5 storey building can be redistributed to differ by 20% between floors, so that the floors have 95%-80%-60%-40%-20% from bottom floor to top floor, respectively. The purpose of this simulation was to see which of the two glazing variations results in better daylight autonomy at the lower floors. These two variations of GWR were also compared to a fully glazed atrium, i.e. 95% glazing on all floors, to test if the benefit of the varied glazing ratio was in fact caused by reflected light of the upper surfaces or only caused by larger windows at the lower floors.



(a) Bottom floor – South **(b)** Bottom floor – North

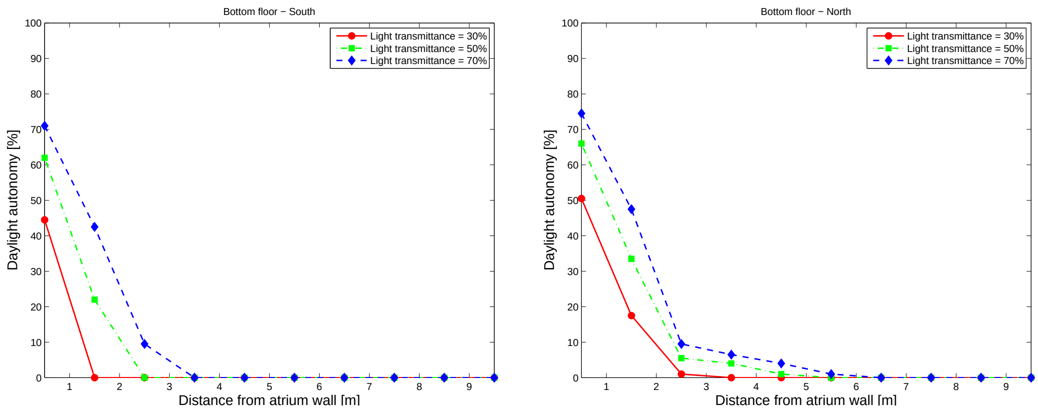
Figure 3.13: Varying the glazing within an atrium will result in increased daylight autonomy due to the reflected component of the light within the atrium.

A not so surprising result is that GWR option 2 results in much lower daylight autonomy at the upper most floors due to much lower glazing ratios, see figure 3.13. This negative difference is however only noticeable at the top two floors. Already at the middle floor, the benefit of varying the glazing ratio is observable. GWR option 2 results in a slightly better daylight autonomy on the middle floors and the floors below it. This goes to show that increasing the area of opaque surfaces at upper levels within the atrium allows for more light to be reflected down into the atrium, see appendix C.15. Another interesting observation of the results is that GWR option 3 with 95% glazing at the upper floors does not result in any better daylight autonomy than GWR option 1 with 60% glazing. In fact, the resulting daylight autonomy of the two GWR options (i.e. options 1 and 3) is quite similar on all floors.

3.9 Light transmittance of glazing

Study question: *What is the impact on the daylight autonomy if the light transmittance of the glazing is altered?*

The light transmittance of glazing will determine the percentage of visible light that will pass through glazing, as was established in section 1.4.2. Daylight autonomy was simulated in the building model with light transmittance of glazing set to 30%, 50% and 70%.



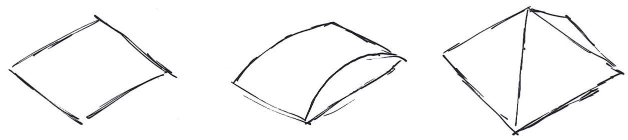
(a) Bottom floor – South slab **(b)** Bottom floor – North slab

Figure 3.14: Daylight autonomy for different light transmittance of atrium windows.

Increasing the light transmittance of the glazing has significant effect on the daylight autonomy within the building as seen in figure 3.14. The results in appendix C.9, show that the effect is quite great regardless of orientation. This implies that when dramatic design solutions, such as sloping the atrium wall or altering the design of the atrium roof are not feasible, a simple solution like increasing the light transmittance of the glazing can go a long way towards a more naturally lit environment. Increasing the light transmittance of glazing can however result in increased risk of glare. Shading devices should therefore be implemented if such risks arise.

3.10 Shape of atrium roof glazing

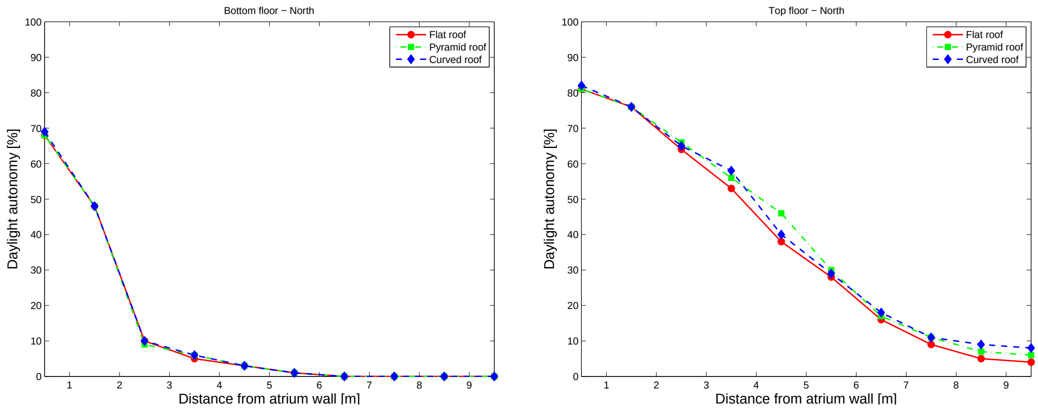
Study question: *Does the shape of a fully glazed roof have any effect on the daylight autonomy of adjacent spaces of the atrium?*



(a) Flat roof **(b)** Curved roof **(c)** Pyramid roof

Figure 3.15: Different atrium roof shapes.

The purpose of this study is to examine how the different shapes, in figure 3.15, of the light transmitting atrium roof surface effect the distribution of natural light in an atrium building. The roofs are modelled without structural elements or other elements that might block the sun.



(a) Bottom floor – North **(b)** Top floor – North

Figure 3.16: Varying shape of the atrium roof glazing has little affect on the daylight autonomy

The results presented in figure 3.16 show that the daylight autonomy does not seem to be affected significantly, at the lower levels of the building, by changing the roof shapes. This is most likely due to the fact that the light which is distributed into the lower floors is mostly diffuse light to begin with. Changing the shape of the light-transmitting roof surface therefore has negligible effect. A slight difference can however be noticed at the upper levels (middle- and top-floors), see appendix C.10. There the extruded glazing shapes (the pyramid shape and the curved shape) give a slightly better result. The reason for this could be that the light breaks slightly when it passes through the glazed roof, thus resulting in more direct light reaching the upper adjacent spaces of the atrium.

3.11 Height of a four sided atrium roof (box)

Study question: *How does the height of a boxed shaped four-sided roof influence the daylight distribution?*

This simulation studied a four-sided, box-shaped atrium roof with glazing on its vertical panels and a closed top, so that light only passes through its side panels.

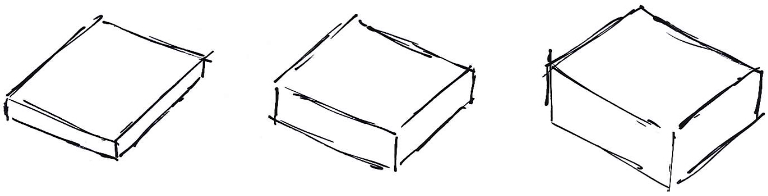
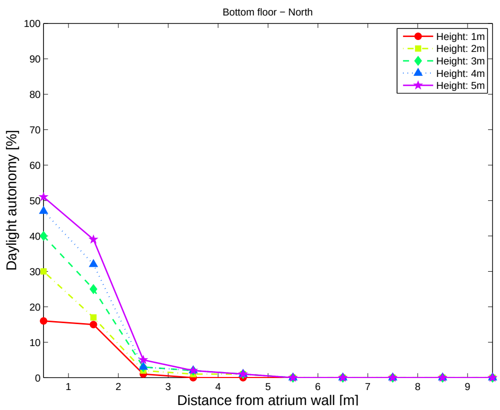
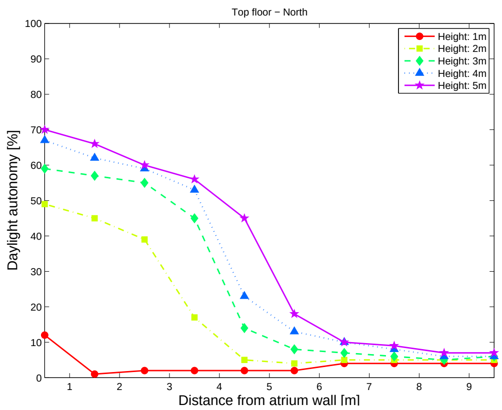


Figure 3.17: The height of the box was raised in increments of 1 m

Raising the height of the box clearly increases the daylight distribution within the building. As can be seen on the nine plots presented in appendix C.11, and figure 3.18, the daylight autonomy converges at box height 4-5 m. A conclusion can thus be drawn that increasing the height more than this will have limited effect. Designers should however keep in mind that raising the height of the box extensively is a unrealistic design option as developers are more likely to add an additional floor to a building (thus increasing rentable space) if they have permission to do so rather than using the height quota for an excessively high atrium. A box-height greater than the average floor-to-floor height within the building is therefore unlikely.



(a) Bottom floor – North



(b) Top floor – North

Figure 3.18: Increasing the height of the box increases the access to daylight and thus increases the daylight distribution within the building. However, a box-height greater than the average floor-to-floor height within the building is unlikely.

3.12 Sawtooth roof orientation

Study question: *Which orientation of a sawtooth roof gives the best daylight autonomy within a building?*

The sawtooth roof was modelled in such a way that it only had glazing on its vertical panels. Other surfaces (top and sides) were opaque. The orientation refers to the orientation in which the glazed surface of the roof faces.

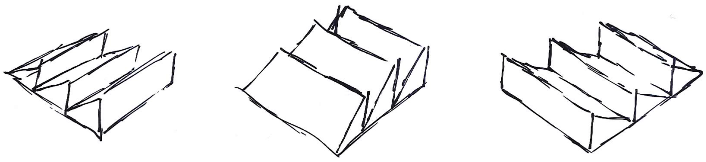
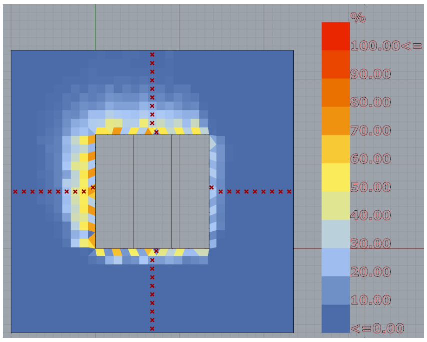
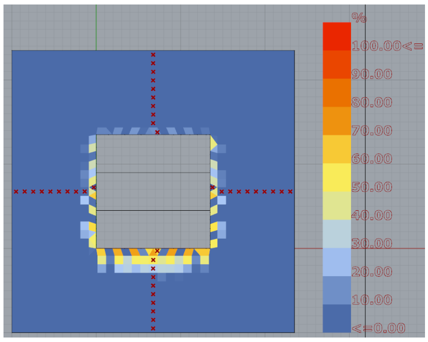


Figure 3.19: Orientations of a sawtooth atrium roof studied.

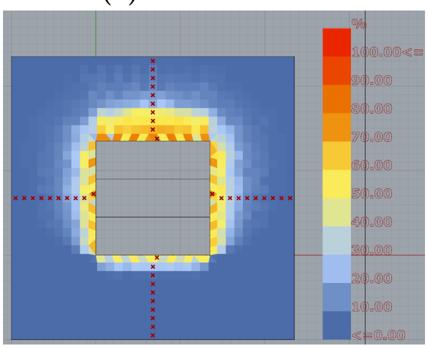
Since this roof-structure only has glazing facing in one direction, the resulting daylit zone is the largest on the opposing side for each orientation, as seen in figure 3.20. Orienting the roof structure such that the glazed panels are faced south offers most access to direct daylight, which in turn results in the best daylight autonomy on the opposite floor plan (i.e. north). The daylight autonomy is however quite poor for other orientations of the floor plan. Facing the roof structure north has the worst overall result, see appendix C.12.



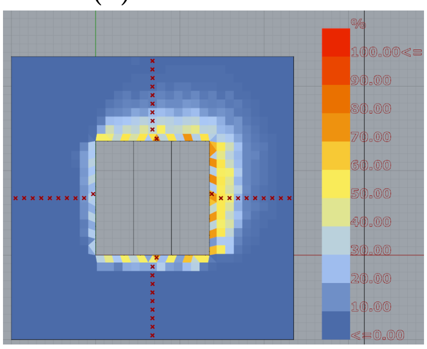
(a) East orientation



(b) North orientation



(c) South orientation



(d) West orientation

Figure 3.20: Daylight autonomy on the top floor for different sawtooth orientations.

3.13 Height of sawtooth roof

Study question: *How does the height of the sawtooth roof effect the daylight autonomy?*

The effect of varying the height of the sawtooth roof, presented in the previous section, was examined in this simulation.

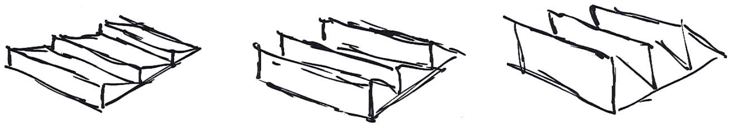
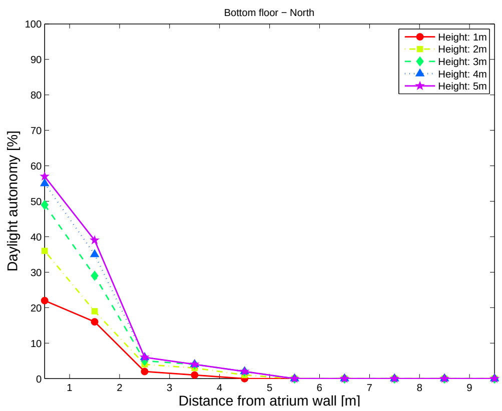
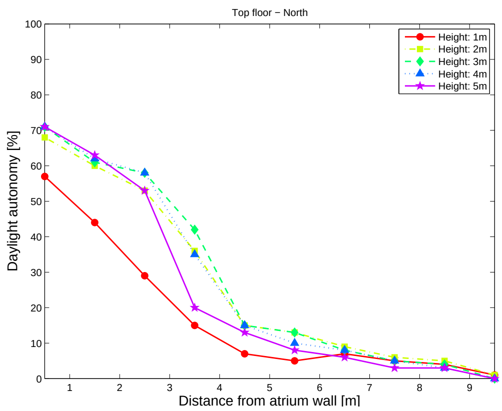


Figure 3.21: The height of a sawtooth atrium roof studied.

Raising the height of the roof clearly increases the daylight distribution within the building as seen in figure 3.22. By studying the results presented in appendix C.13, it can be seen that the daylight autonomy converges at sawtooth height 4-5 m. A conclusion can thus be drawn that increasing the height more than this will have limited effect. Designers should however keep in mind that raising the height of the roof extensively is a unrealistic design option as developers are more likely to add an additional floor to a building (thus increasing rentable space) if the have permission to do so rather than using the height quota for a very high atrium. A roof-height greater than the average floor-to-floor height within the building is therefore unlikely.



(a) Bottom floor – North



(b) Top floor – North

Figure 3.22: Daylight autonomy on the top and bottom floor of the northern slab for different sawtooth heights.

3.14 Comparing different atrium roof types

Study question: *How does the atrium roof type affect the daylight distribution in the adjacent spaces, and which roof shape offers the most daylight autonomy?*

The results from previous simulations of roof types are compared here to get a better idea of which roof type is the best. Previous study questions showed that the glazing shape does not have significant effect on the daylight autonomy, hence the standard flat shape is chosen for this comparison. Furthermore a south-facing sawtooth roof with a height of 3 meters is compared as it was argued that heights greater than this would be an unlikely design approach. Similarly a box roof with a height of three meters is compared.

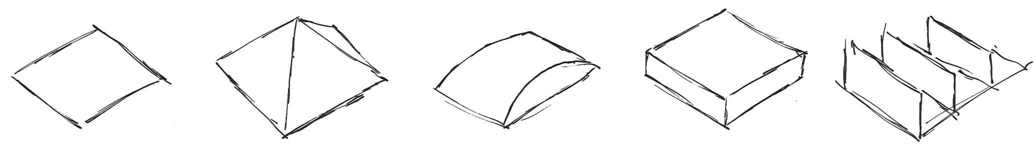
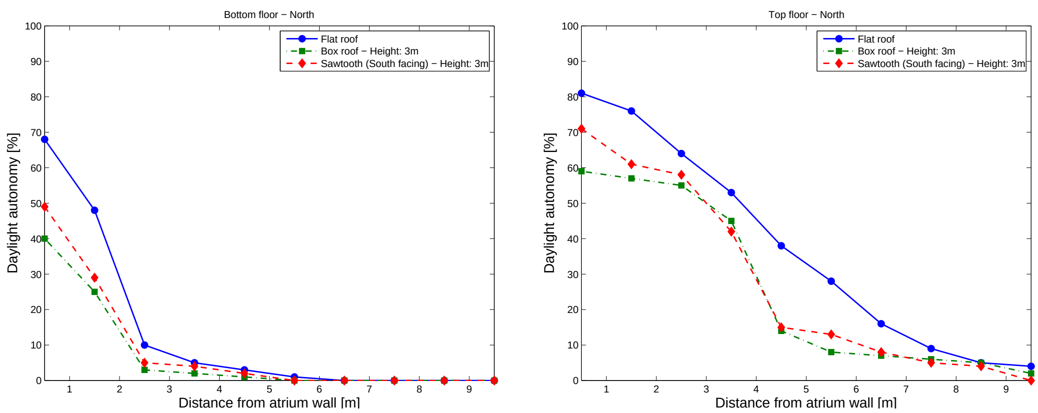


Figure 3.23: The different roof types studied (flat, pyramid, curved, box, and sawtooth).

Although the flat roof gives the highest daylight autonomy, it does not reach significantly further into the floor plan of the lowest floors as seen in appendix C.14. The daylight autonomy decreases almost linearly on the northern top floor as seen in figure 3.24b.



(a) Bottom floor – North

(b) Top floor – North

Figure 3.24: The different roof types studied compared.

3.15 A discussion on the depth of daylight zones

How can the results obtained from the simulations help decide the layout of an open plan building? One way of reducing the need for artificial lighting is to bring the task to the light, i.e. the zones within the floor plan that are richer in natural daylight should be utilized as areas that are generally more occupied. Consequently, the use of artificial lighting can be reduced in these zones. Table 3.1 shows how deep daylight autonomy $\geq$ 50%[34] can potentially reach within each of the studied floor plans. Results from the following five simulations were evaluated for this purpose and the average depth compared to the depth of the standard model:

A) Reflectance of atrium walls (section 3.4)

B) Sloping the atrium walls (section 3.5)

C) Glazing convergence (section 3.7)

D) Varying the glazing ratio (section 3.8)

E) Increasing light transmittance of glazing (section 3.9)

Table 3.1: The potential depth, in meters, of the $\geq$ 50% daylight autonomy for the five of the simulations. The average depth of each floor is given for the North, South and East orientation, as well as the depth of the daylit zones of the standard model.

[m]	Top floor							Middle floor							Bottom floor						
	A	B	C	D	E	Avg.	Strd.	A	B	C	D	E	Avg.	Strd.	A	B	C	D	E	Avg.	Strd.
South	2,7	4,0	3,5	3,0	2,7	3,2	2,5	2,2	3,5	2,5	2,5	2,2	2,6	2,0	1,6	3,2	2,0	2,0	1,6	2,1	1
North	4,1	6,0	5,5	5,5	4,1	5,0	4,0	2,5	4,5	3,0	3,0	2,5	3,1	2,5	1,8	3,0	2,0	2,2	1,8	2,2	1,2
East	3,0	4,0	5,0	3,1	3,0	3,6	3,0	2,5	4,0	2,8	2,8	2,5	2,9	2,0	1,8	3,0	1,8	2,1	1,8	2,1	2,1

It is clear that the daylight from the atrium alone will not suffice for a good quality daylit environment. Daylight from a façade which is free of obstructions will generally reach much further into a zone, up to 9 m as was mentioned in the literature review section of this thesis. By implementing the design solutions studied in the previous sections, the daylight from an atrium can however help increase the daylight within a room. As seen in table 3.1, the depth of the daylit zones from the atrium can be increased by up to two meters compared to the standard model. On average all the design solutions studied have potential for increasing the depth of the daylit zones. It is therefore evident that certain parameters within the atrium can be altered to increase daylight within a building.

[34] DA = 50% is chosen here in accordance to LEEDv4 where illuminance must be over 300 lux for 50% of the annual occupancy hours (see section 1.6.4).

Chapter 4: Conclusion

4.1 Conclusion

Simulations showed that several design factors give potential for increasing the daylight autonomy in the adjacent spaces of atria. Evaluation of the base shape of an atrium showed that a circular atrium will have the most uniform daylight distribution, while it was thought that the atrium shape should reflect the building shape as it would reduce large zones with low daylight autonomy.

Increasing floor-to-ceiling heights will slightly increase daylight autonomy within the building floor plan, although the effect was not as great as expected from Saxon's statement which was presented in the literature review.

Simulation of the number of floors of an atrium building verified previous research which had stated that the lower the well index, the more access to daylight can be found at the lower levels of a building. Hence, it was established that an atrium can theoretically be infinitely high as long as the well index is kept at a reasonably low value (e.g. < 1.0).

Increasing the access to the sky within an atrium, by making the atrium wider at its top than at its base, was found to have dramatic effect on the daylight autonomy on all floor plans within the building. Doing the opposite, i.e. making the atrium narrower at its top than at its base resulted in much lower levels of daylight autonomy. An atrium with a variation of forward leaning and backward leaning atrium walls therefore had very uneven distribution of daylight autonomy depending on the slope of the atrium wall.

Daylight autonomy was found to converge at glazing-to-wall ratios (GWR) set to 65 – 75%, and gradually decrease with higher GWR, due to a reduction in reflected light within the atrium. Varying the ratio of glazed to opaque material within the atrium, by increasing the reflective surfaces in the upper part of the atrium,resulted in better daylight autonomy at lower floors. Combining these solutions with glazing with higher light transmittance also resulted in noticeable increase of daylight autonomy.

The shape of a fully glazed atrium roof was not found to have significant effect on the daylight distribution on any floors within the building, while the design of a more diffuse roof structure resulted in very different daylight autonomy depending on the design of the roof. Increasing the height of a four sided atrium box increased the access to daylight and thus increased the daylight distribution within the building, which was found to converge at a height of $4 - 5\,\mathrm{m}$. Simulations of a differently oriented sawtooth roof structure showed that facing the glazing of a sawtooth roof-structure towards south gives the best daylight autonomy since it receives most direct daylight on an annual basis. The benefits of this orientation are however mainly noticeable on the North facing floor plan. Of the simulated roof types, a fully glazed roof resulted in the highest daylight autonomy.

From the above stated conclusions it can be established that as the light reaches further down into an atrium, the reflective component of the light becomes increasingly important. It is therefore crucial to use high reflective, light coloured surfaces within the atrium, while also keeping the reflective surfaces free of obstructions such as balconies, protruding fixtures, or forward leaning walls. Failing to fulfil this will highly decrease the daylight distribution at lower levels adjacent to the atrium. Design aspects to keep in mind in the early stage design of atria to increase daylight autonomy thus include:

- The atrium shape should follow the shape of the building to minimize zones with low daylight autonomy
- Increase floor-to-ceiling heights to obtain a slight increase in daylight autonomy.
- Use walls with high reflectance within the atrium and maximize the area of reflective surfaces at upper parts of atria to increase the reflected light at lower floors.
- Keep windows within the atrium free of obstructions
- Maximize view of sky with e.g. tall windows and/or by sloping atrium walls
- Increase light transmittance of glazing
- The atrium roof should have as much glazing as possible
- Vary the glazing within an atrium so that more glazing is found at the lower levels than at upper levels.
- Keep the well index as low as possible

As daylight studies move more towards computer based simulations rather than physical models, and certifications, such as the ones mentioned in this thesis, put more emphasis on annual simulations, user friendly tools for daylight simulation become increasingly important. The simulations conducted in this research have shown that the ability to perform dynamic daylight simulations for early stage design is quite feasible, thus backing up previous research and comparisons between computer based simulations and physical models. The tools used in this study showed outstanding integration between the modelling tool and daylight simulation tool.

The guideline document, presented in the next section, in which the results of this thesis have been compiled, allows the architect to study each and every case individually, in detail or by brief observation.

4.2 The guideline document

The results presented within chapter 2.13 have been compiled into a document which is to serve as guidelines for the architects at White Arkitekter, as was explained in section 1.2. The guideline document, titled *Atria – Early Stage Design Guidelines for Daylight Optimization*, has been formulated in such a way that it is accessible to those that do not want to linger on technical detail, while also providing technical information for those who wish to study every question in more detail. In the document, colour coding is used to separate the question from the answer and result interpretation. The colour red is used to highlight the stated question of each simulation, while the colour black is used for more informative text and result interpretation. Finally, the colour green is used to highlight a brief answer to the stated question. Wherever applicable, a hand drawn sketch is given of the parameter associated with the question. Immediately after the given answer to the question, a technical analysis is given of the simulated parameters with comparative Matlab-generated plots, followed by a more graphical representation for visual understanding. The graphical representation is made with screen-shots of the resulting daylight autonomy on floors of interest. An example is given for one study question in appendix D.

The document also starts by stating its purpose and explaining in which manner the models were created, as well as giving explanation of how the results are interpreted. Furthermore some general daylighting rules of thumb are given (for practical reasons), followed by an introduction of daylighting in certifications.

Figure 4.1: The cover page of the guideline document.

4.3 Future work

The design parameters studied, and the questions answered, in the simulations related to this thesis are not comprehensive for the many different aspects that affect daylight autonomy of atria buildings. The document which has been created to represent the results of this research, has potential to grow and expand even further with additional simulations and literature review. This thesis only studied how the various design parameters of atria affect daylight autonomy within a standardized building model. The author proposes that the parameters studied on the standardized model be applied to an existing atrium building, both to verify the accuracy of the simulations and to give better understanding of the influence of these parameters. As a direct continuation of this thesis work, a tutorial on how to setup and perform daylight simulations within Honeybee and Grasshopper will be created for WHITE Arkitekter.

Appendix A

Daylight simulation software assessment

The following text and table offers an assessment of a few simulation tools used for daylighting simulations.

Simulation software introduction

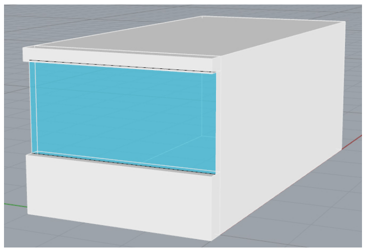
There are many daylighting software available, and using a combination of several tools, although time consuming, is not uncommon. Many factors influence the outcome of the simulations such as the calculation method being used, the sky model, the building model, the surface properties and the users expertise. [26] One thing to keep in mind is that the daylight programs are as diverse as they are many. Some offer a more user friendly interface while others are more robust but not as accessible. There is also a great difference in simulation time between programs, and even the opportunity of accessing the data and studying it after simulation differs quite a lot. It is therefore a relevant question to ask, which simulation tool offers the most accurate and qualitative results, while remaining user friendly? This can differ between projects and really comes down to which indicators are to be studied and how the simulation results are to be presented. Five tools used, or related to tools used, in practice at White Arkitekter, Velux, Autodesk Ecotect, RadianceIES, Diva and Honeybee, have thus been compared in detail.

Although **Velux** uses an optimized method of daylight analysis called bidirectional ray-tracing (a combination of forward and backward ray-tarcing) it only offers modelling of simple geometry or import of 3D objects from another source program (e.g. Revit, CAD, SketchUp, etc.) **Ecotect** offers the possibility of more complex modelling, but lacks the accuracy of results (which can however be optimized if integrated with Daysim and Radiance, see video-links 2 and 4). **RadianceIES** is a detailed 3D simulation tool designed to predict daylight, and the appearance of internal spaces prior to construction. The simulation results can however only be viewed as image files, but the simulations can be directly incorporated with BREEAM. Diva is used as a plug-in for the 3D modelling tool *Rhino*, and can thus be used together with the parametric modelling extension for Rhino called *Grasshopper*. Users of the DIVA plug-in can then construct a one-zone volume for energy analysis based on the existing detailed architectural geometry (and/or import geometry from external 3D programs such as Revit, SketchUp, etc.). Schedules generated by the daylighting analysis are then automatically shared with the energy simulation. This method allows the rapid visualization of daylight and energy consequences from an architectural design model where users can easily test multiple design variants for daylight and energy performance without manually exporting to multiple software. The schedules are automatically saved into *comma separated value* (CSV) files which can be used as inputs into more complex energy models. **Honeybee** works explicitly with *Grasshopper* and gives the user even more control over material creation than with DIVA and also offers multiple components for result visualisation. Another advantage to Honeybee is that it allows simulation of multiple zones in comparison to DIVA'S single zone approach. [27, 50, 59]

The answer to the previously stated question thus depends entirely on the users intention and complexity of the model being analysed. A comparison of a daylight factor simulations carried out on a simple room in each of the programs[1] showed that Velux is without a doubt the easiest tool to use on a simple existing architectural model, but DIVA or Honeybee are a much better choice if an architectural model is intended to be optimized for daylight (or energy) since it can be used with parametric modelling and does not need multiple sub-applications to get a final result. They do however require the user to be familiar with the Grasshopper environment.

[1] See next section

Test room simulation



A simple room was modelled in each of the simulation programs and the average daylight factor calculated over the working plane (0.8 m). Results were quite similar between simulation software for the assigned geometry and material properties except for in Ecotect. There the results showed to be highly optimistic. This coincides with the comparison made by the *Danish Building Research Institute*. [26] In Velux and RadianceIES it seems that the simulation quality depends on the rendering detail of the output, while in Honeybee and Diva, the simulation quality depends on the level of accuracy in the calculation method (depending on the chosen Radiance parameters, see section 2.13) which explains the rising DF-values.

Geometry	
Room depth:	6 m
Room width:	3 m
Room height:	2.5 m
Window area:	$1.5 \times 2.8\,\mathrm{m}^2$
Floor to window height:	0.9 m

Material properties				
	Floor	*Ceiling*	*Walls*	*Window*
Reflectance	0.65	0.84	0.84	–
Roughness	0.03	0.03	0.03	–
Specularity	0.20	0.00	0.00	–
Light transmittance	–	–	–	0.70

Program		Quality settings: Low	Medium	High
Velux	Simulation time (min)	00:03	03:50	11:04
	Min DF (%)	0,78	0,87	0,89
	Max DF(%)	16,47	16,14	16,06
	Avg. DF (%)	3,64	3,68	3,67
	Miljöbyggnad DF (%)	2,00	2,00	2,00
Honeybee	Simulation time (min)	00:09	02:55	12:49
	Min DF (%)	0,34	0,96	2,17
	Max DF (%)	16,67	18,02	19,11
	Avg. DF (%)	3,43	4,45	5,81
	Miljöbyggnad DF (%)	2,29	2,29	3,76
Diva	Simulation time (min)	00:04	03:31	07:20
	Min DF (%)	0,58	1,37	2,23
	Max DF(%)	7,12	8,73	10,15
	Avg. DF (%)	3,01	4,10	5,47
	Miljöbyggnad DF (%)	2,63	3,64	4,98
Ecotect	Simulation time (min)	00:03	00:30	02:37
	Min DF (%)	4,59	4,22	4,18
	Max DF (%)	25,16	23,03	21,60
	Avg. DF (%)	8,66	8,12	7,40
	Miljöbyggnad DF (%)	6,04	6,28	6,71
RadianceIES	Simulation time (min)	00:24	01:00	34:03
	Min DF (%)	0,06	0,73	0,71
	Max DF(%)	22,04	19,06	19,58
	Avg. DF (%)	3,63	4,00	3,89
	Miljöbyggnad DF (%)	1,10	1,10	1,80

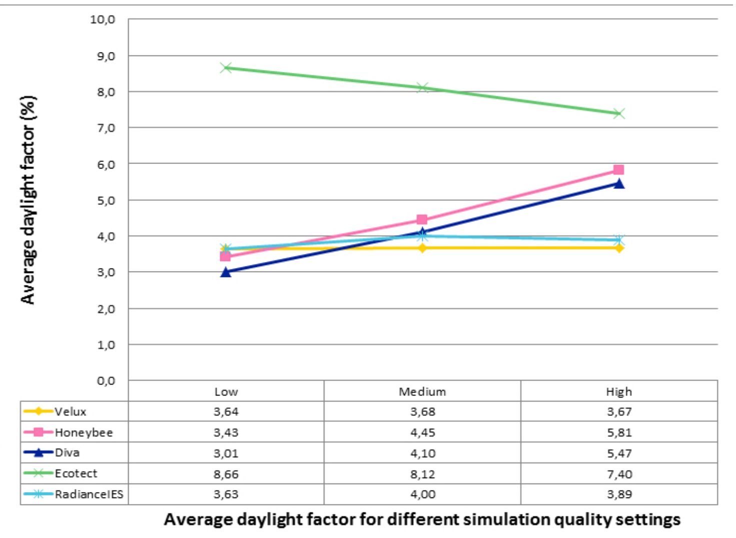
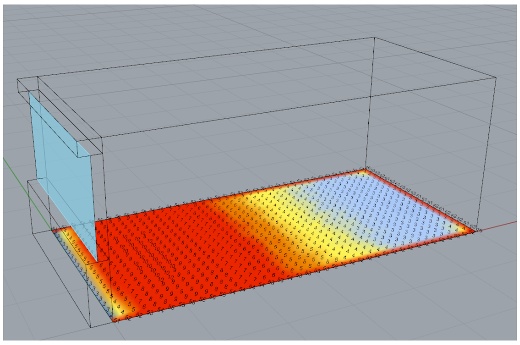


Figure A.1: The graf shows the average daylight factor for different simulation quality settings within each of the studied simulation programs. In the adjacent table relevant DF values are compared. The *Miljöbyggnad DF* refers to the value at half the room depth, one meter from the darkest wall.

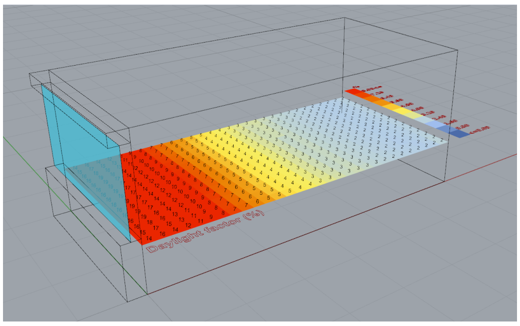
When the DF according to Miljöbyggnad (MB) is compared between the tools, it can be seen that Ecotect is highly optimistic while RadianceIES gives slightly lower results than the other three tools. Results from Velux do not change with increased quality while Honeybee and Diva give increased DF-values.

Diva simulation



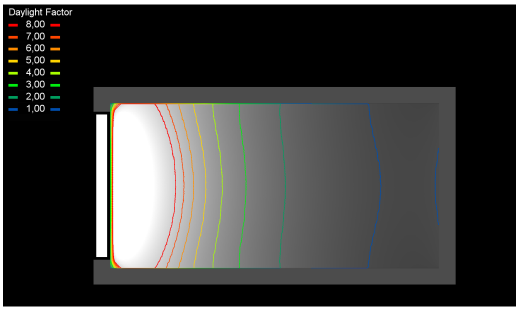
The results from Diva are directly observed in the Rhinoceros 3D environment. A color mesh represents the daylight factor distribution and values can be directly observed within each mesh face of the analysis plane. The user controls the accuracy in the results by setting the mesh size of the analysis plane and simulation quality. Leakage occurs along adjacent surfaces in Diva when they are modelled as single pane objects.

Honeybee simulation



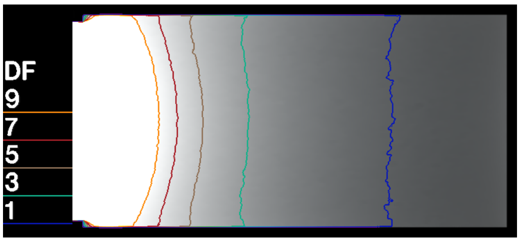
The results from Honeybee are directly observed in the Rhinoceros 3D environment. Result presentation are the same as in Diva. The user controls the accuracy in the results by setting the mesh size of the analysis plane and simulation quality. Calculation parameters have been optimized in honeybee to reduce eliminate leakage along adjacent surfaces.

Velux simulation



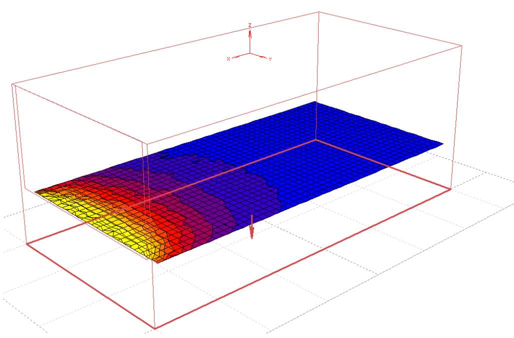
Velux offers a 2D result presentation of the daylight factor with either isocurves or falsecolor images.

RadianceIES simulation



RadianceIES offers a 2D result presentation of the daylight factor with either isocurves or falsecolor images.

Ecotect simulation



Results from Ecotect are directly observed within the model. Result presentation is in the form of a color-grid and mesh values can be toggled on and off. Point values on the grid can also be exported as text-files.

Useful tutorials

The following, are links to several video-tutorials explaining the basics of the different softwares:

1. Daysim with SketchUp: http://www.youtube.com/watch?v=yBTMsH6i0KI
2. Daysim with Ecotect: http://www.youtube.com/watch?v=DNwGT8Lm-3Q
3. Daylight simulations with Ecotect: http://www.youtube.com/watch?v=Q6lQec01AWc
4. Radiance with Ecotect: http://www.youtube.com/watch?v=T9dZwQ-La8Y&feature=player_embedded
5. BIM daylight analysis using Ecotect: http://sustainabilityworkshop.autodesk.com/buildings/daylight-analysis-bim
6. Daylight simulation in IESVE: http://www.youtube.com/watch?v=WWpDQSqODRQ
7. Three dimensional daylight visualisation using Diva with Grasshopper: http://www.youtube.com/watch?v=-Fb0FBF9NdQ
8. Diva daylight simulation with Rhinoceros 3D: http://vimeo.com/85968006
9. Velux Daylight Visualizer: http://www.youtube.com/watch?v=q3JI4rFi-wc
10. Daylight simulations with Honeybee: http://www.youtube.com/watch?v=o5WNxkgL0hc

Table footnotes

1. File types that the author has knowledge about that can be imported. Other file types might be imported as well.
2. .3dm, .rws, .3ds, .ai, .dxf, .x, .eps, .off, .gf, .gft, .gts, .igs, .iges, .lwo, .dgn, .fbx, .scn, .obj, .pdf, .ply, .asc, .csv, .txt, .xyz, .cgo_ascii, .cgo_asci, .raw, .m, .skp, .slc, .sldprt, .sldasm, .stp, .step, .stl, .vda, .wrl, .vrml, .dgf, .zdr
3. The average daylight factor can be accessed on all the programs.
4. Glare simulations can be made for visual comfort evaluations in Diva, Honeybee and RadianceIES. The outputs are image-based with glare values on surfaces.
5. Can be achieved by extracting values from the result files.
6. Daylight factor simulations were carried out on a simple room in all the programs and the average daylight factor compared. The rating is given as 1 (optimistic= for tools that gave higher DF, 3 (moderate) for tools with similar values, and 5 (unoptimistic) for tools with low values. Note that the results for Diva, Honeybee and RadianceIES become more optimistic with increased simulation accuracy.
7. A rating of how much the results can be manipulated after simulation.
8. Once the user has gained experience in Rhino and/or Grasshopper, using the user-interface becomes quite easy.

Table A.1: Software assessment table. [26, 37, 48, 50]

	Diva for Rhino and Grasshopper	**Honeybee for Grasshopper**	**Velux Daylight Visualizer**	**RadianceIES (IESVE)**	**Daysim**	**Autodesk Ecotect**
Simulation engines	Radiance, Daysim, EnergyPlus, Evalglare, Wxfalsecolor	Radiance, Daysim, EnergyPlus, Evalglare, Falsecolor2, OpenStudio	Luxion	Radiance	Radiance	Ecotect
Calculation method	Backward raytracing	Backward raytracing	Bi-directional raytracing with photon mapping and irradiance caching	Backward raytracing	Backward raytracing	BRE split flux
Compatibility						
Stand alone?	No	No	Yes	Yes	No	Yes
Plug-in?	Yes (for Rhino and Grasshopper)	Yes (for Grasshopper)	No	No	Yes (for SketchUp, Ecotect and Rhino)	No
Open source?	No	Yes	No	No	Yes	No
Licence						
License needed?	Yes	No (free)	No (free)	Yes	No (free)	Yes
Student license?	Yes	–	–	Reduced price	–	Yes
Setup / Input						
Sky types	– CIE clear sky with sun – CIE overcast sky – Clear sky without sun – CIE uniform sky – Climate based sky – Custom sky (Perez)	– CIE sunny with sun – CIE sunny without sun – CIE intermediate with sun – CIE intermediate without sun – CIE uniform sky – CIE cloudy sky – Climate based sky	– CIE overcast sky – CIE intermediate sky – CIE clear sky	– Sunny sky – Standard clear sky – CIE overcast sky – Intermediate with sun – Intermediate without sun – Uniform cloudy sky – 10K lux CIE overcast sky	– CIE clear sky with sun – CIE overcast sky – Clear sky without sun – CIE uniform sky – Climate based sky – Custom sky (Perez)	– CIE overcast sky – CIE uniform sky – Other sky types available when used with Daysim
Geometric modelling within the program	Yes (with Rhino or Grasshopper)	Yes (with Rhino or Grasshopper)	Yes	Yes	No	Yes
Import of geometric model in the program	Yes, through Rhino	Yes, through Rhino	Yes	Yes	Yes, through the host program	Yes
Import file types [1]	CAD based fil-types (.obj, .skp, .dwg, .dxf, .3dm,...[2])	CAD based fil-types (.obj, .skp, .dwg, .dxf, .3dm,...)	.obj, .skp, .dwg, .dxf	gbXML, IFC	Depends on the host program	.obj, .skp, .dwg, .dxf

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	Diva for Rhino and Grasshopper	**Honeybee for Grasshopper**	**Velux Daylight Visualizer**	**RadianceIES (IESVE)**	**Daysim**	**Autodesk Ecotect**
Output						
Daylight factor [3]	Yes	Yes	Yes	Yes	Yes	Yes
Illuminance	Yes	Yes	Yes	Yes	Yes	Yes
Glare / Luminance [4]	Glare and luminance	Glare and luminance	Luminance	Glare and luminance	Luminance	Luminance
Uniformity	Can be calculated	Can be calculated	Yes	Yes	Yes	Yes, if used with RADIANCE and DAYSIM
Daylight autonomy	Yes	Yes	No	Yes	Yes	Yes
Continuous daylight autonomy	Yes	Yes	No	No	Yes	No
Spatial daylight autonomy	No [5]	Yes	No	Yes	Yes	Yes, if used with DAYSIM
Annual sunlight exposure	Can be calculated by extracting values from the result files	Can be calculated by extracting values from the result files	No	Yes	Yes	Yes, if used with DAYSIM
Useful daylight illuminance	Yes	Yes	No	No	Yes	Yes, if used with RADIANCE and DAYSIM
Results						
Optimism of results [6]	3	3	5	3	–	1
Results accessibility [7]	1	1	4	4	2	3
Format of results	Image files, csv text files, DAYSIM report	Image files, csv text files, DAYSIM report	Image based and HTML report	Image based	Image files, csv text files, DAYSIM report	Image files and csv text files
Timelapse images	Yes	Can be modelled	Yes	No	No	No
User friendlyness						
Preparation difficulty	3 (Rhino and/or Grasshopper experience required [8])	3 (Rhino and/or Grasshopper experience required)	1	2	3 (RADIANCE experience required)	2
Simulation time	Simulation time will always depend on the complexity of the model and level of detail. Honeybee offers simultaneous multi-zone simulation which means that simulation time is reduced as the program does not need to be set up for each individual zone. The simulation time is quite similar between programs for a single zone model.					

Very easy/good (1); Easy/good (2); Moderate (3); Difficult/bad (4); Very difficult/bad (5)

Appendix B

Study questions

This appendix includes the study questions formulated from the hypotheses established in section 2.6.

1. How does the base shape of the atrium (i.e. square, triangular, or circular) affect the daylight distribution in the adjacent spaces?
2. Will increasing the floor-to-ceiling height result in better daylight autonomy on all floors?
3. How high can a building theoretically be in order for an atrium to give any daylighting benefits at the lowest floors?
4. How does the reflectance of the atrium surfaces affect the daylight autonomy at the lowest floors adjacent to the atrium?
5. How does the slope of atrium walls affect the daylight autonomy, and which shape gives more daylighting benefits, V-shape or A-shape?
6. How does the slope of atrium walls affect the daylight autonomy when the atrium shape is made to be narrower (X-shape) or wider (◇-shape) at its center than at its top and bottom?
7. Is there a certain glazing-to-wall ratio (GWR) after which increasing the GWR will not increase the daylight autonomy?
8. Does varying the ratio of glazing to opaque material per floor in the atrium well result in better daylight autonomy at lower floors?
9. How does the daylight autonomy change by altering the light transmittance of the glazing?
10. Does the shape of a fully glazed roof have any effect on the daylight autonomy within the building?

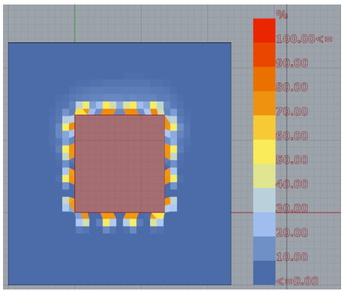
11. How does the height of a four sided box-shaped roof influence the daylight distribution?
12. Which orientation of a one sided sawtooth roof gives the best daylighting benefits within a building?
13. How does the height of a one-sided sawtooth roof affect the daylighting benefits within the building?
14. How does the atrium roof type affect the daylight distribution in the adjacent spaces of an atrium, and which roof shape offers the best daylighting benefits?
15. What is the typical depth of illuminance zones and how can that influence the positioning of spaces in need of good light?

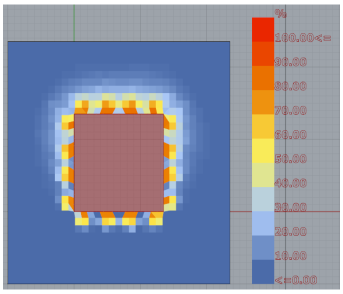
Appendix C

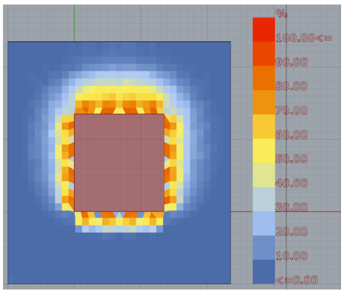
Results from simulations

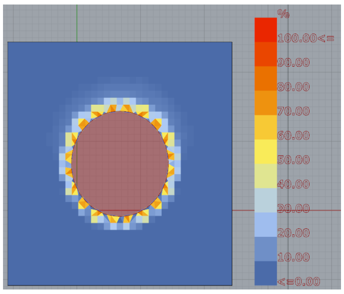
This appendix includes results from the daylight simulations. First 9 graphs are given for 3 orientations for all floors of interest, followed by a graphical visualisation of the gradient colour mesh of the floors (wherever relevant) to give a notion of the overall daylight autonomy distribution. Each section within this appendix includes the result for one study question.

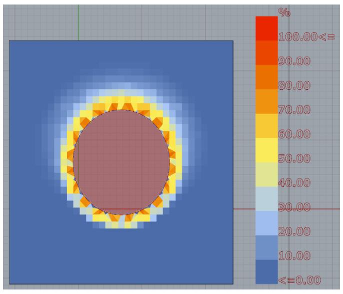
C.1 Atrium Shape

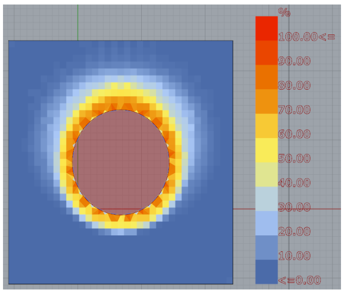

(a) Bottom floor

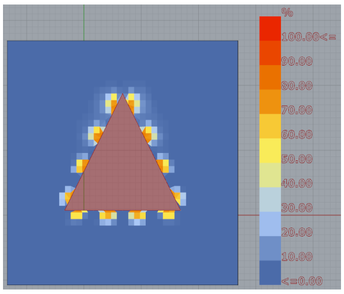

(b) Middle floor

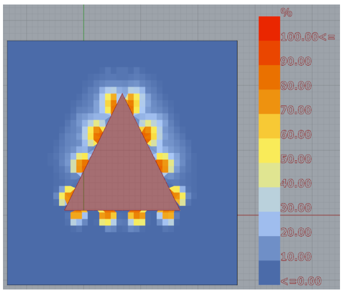

(c) Top floor

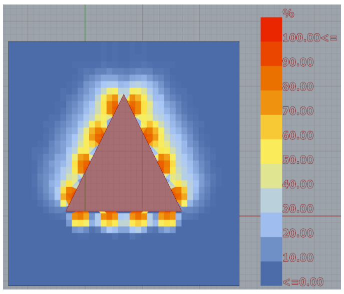

(d) Bottom floor

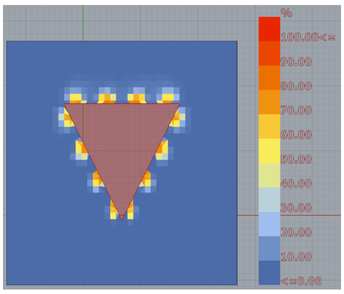

(e) Middle floor

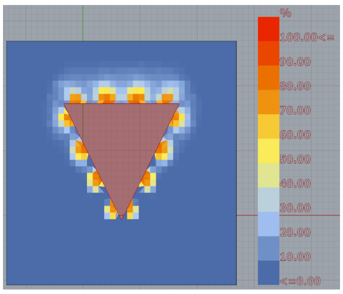

(f) Top floor


(g) Bottom floor


(h) Middle floor


(i) Top floor


(j) Bottom floor


(k) Middle floor

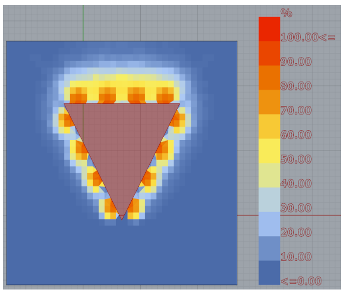
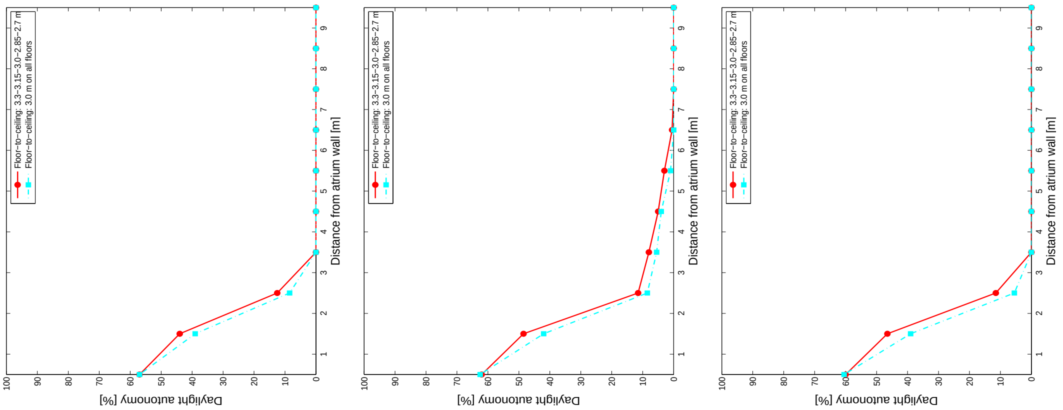
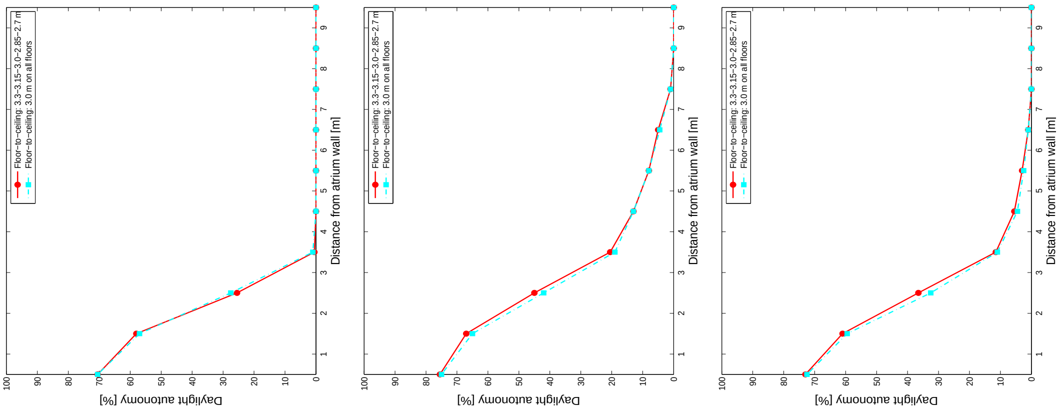

(l) Top floor

Figure C.1: Daylight autonomy distribution on the bottom, middle, and top floor of the spaces adjacent to four different atrium shapes.

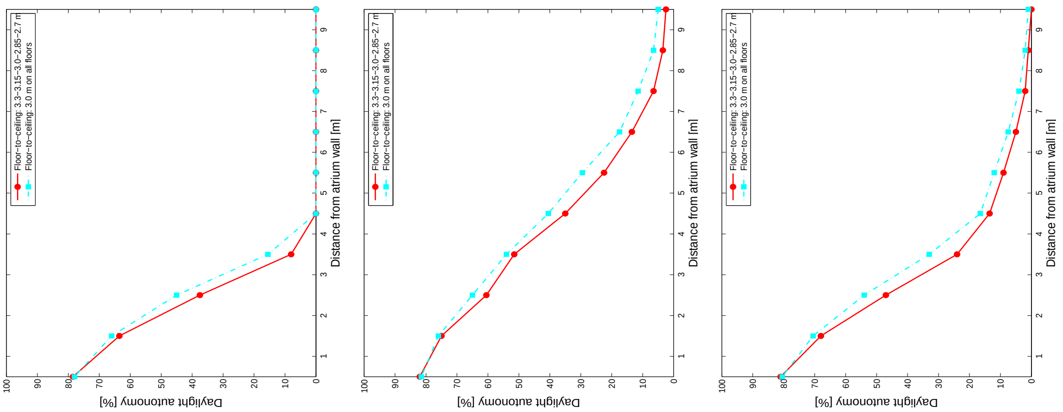
C.2 Floor-to-ceiling height



(a) Bottom floor – South **(b)** Bottom floor – North **(c)** Bottom floor – East



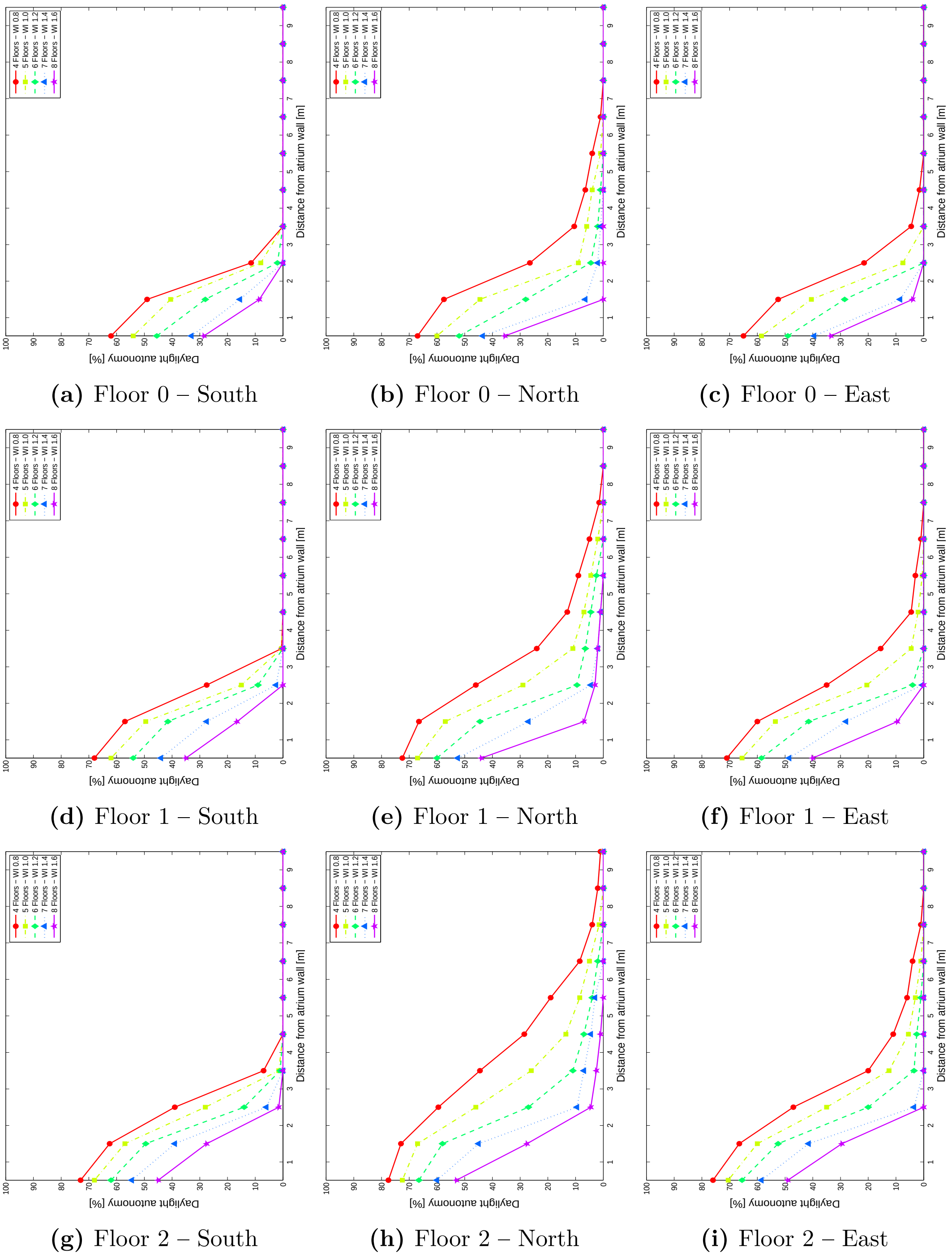
(d) Middle floor – South **(e)** Middle floor – North **(f)** Middle floor – East



(g) Top floor – South **(h)** Top floor – North **(i)** Top floor – East

Figure C.2: Daylight autonomy for different floor-to-ceiling heights.

C.3 Number of floors

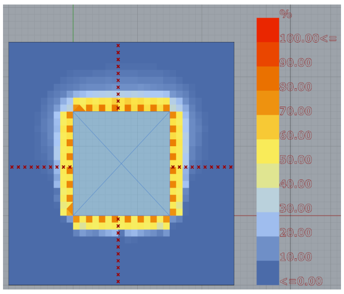


(a) Floor 0 – South **(b)** Floor 0 – North **(c)** Floor 0 – East

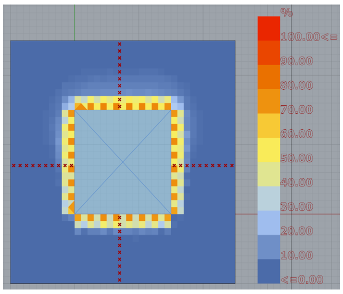
(d) Floor 1 – South **(e)** Floor 1 – North **(f)** Floor 1 – East

(g) Floor 2 – South **(h)** Floor 2 – North **(i)** Floor 2 – East

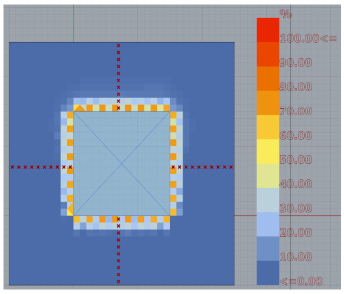
Figure C.3: Simulation result for increasing number of floors. The plots show the daylight autonomy along a center-line reaching from the atrium wall towards the façade.



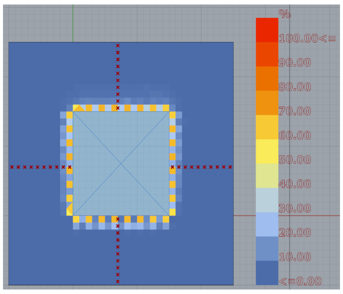
(a) 4 floors – Floor 0



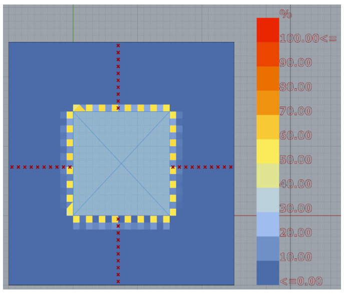
(b) 5 floors – Floor 0



(c) 6 floors – Floor 0



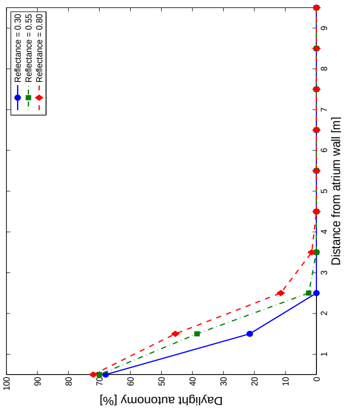
(d) 7 floors – Floor 0



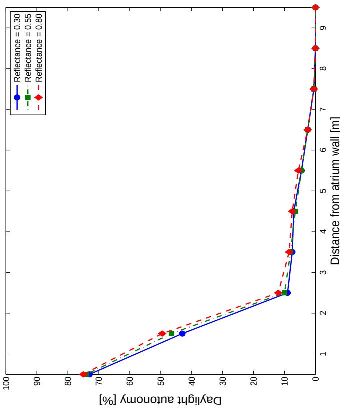
(e) 8 floors – Floor 0

Figure C.4: Daylight autonomy distribution on the bottom floor of each building (4, 5, 6, 7, and 8 floors, respectively).

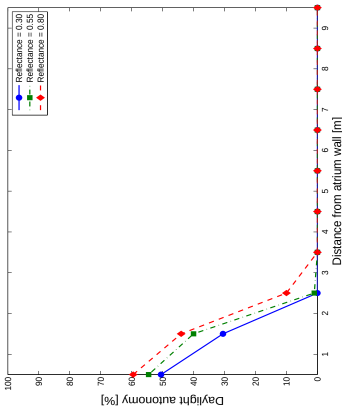
C.4 Reflectance of atrium walls



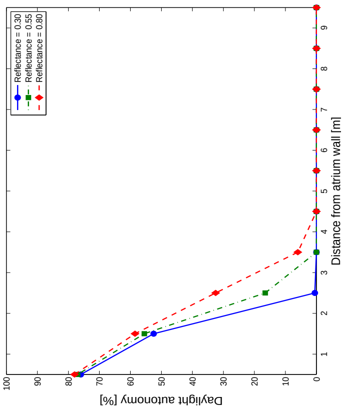
(a) Bottom floor – South



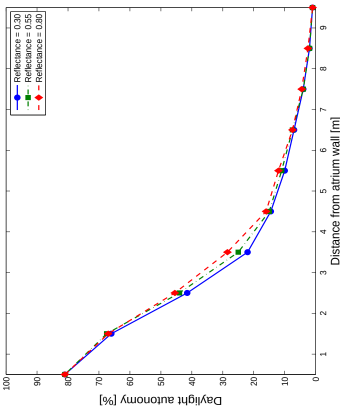
(b) Bottom floor – North



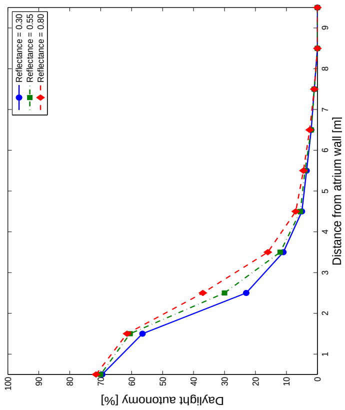
(c) Bottom floor – East



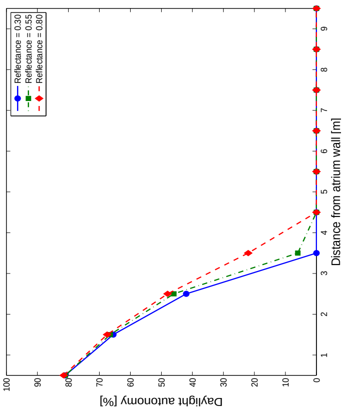
(d) Middle floor – South



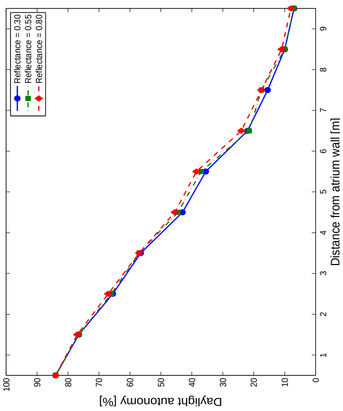
(e) Middle floor – North



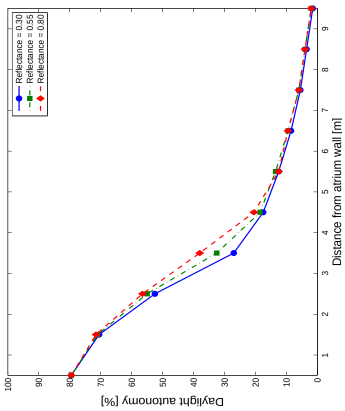
(f) Middle floor – East



(g) Top floor – South

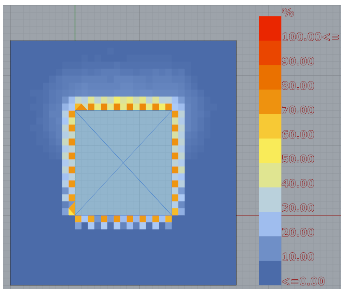


(h) Top floor – North

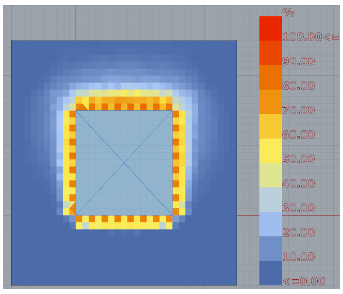


(i) Top floor – East

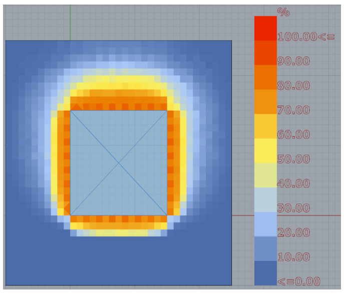
Figure C.5: Increasing the reflectance of the atrium walls increases the daylight autonomy on the orientations that receive less direct daylight, i.e. South, East, and West. A limited increase in daylight autonomy can be noticed on the North side.



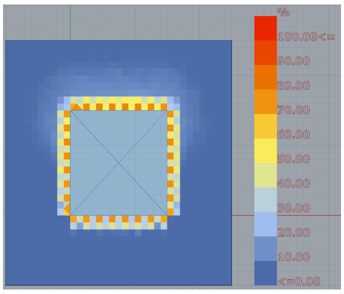
(a) Bottom floor – Refl. = 30%



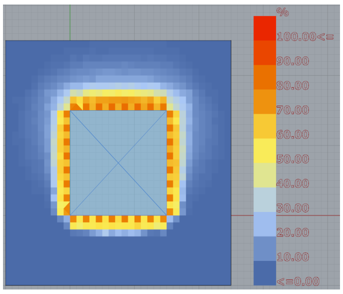
(b) Middle floor – Refl. = 30%



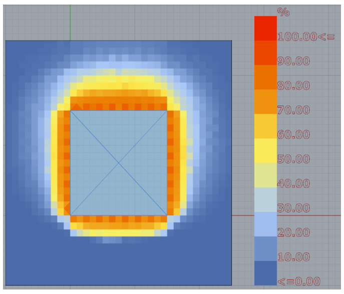
(c) Top floor – Refl. = 30%



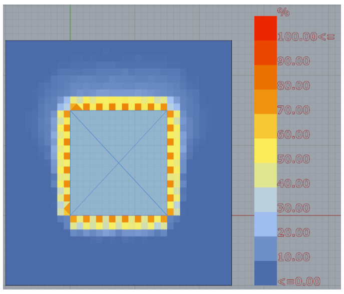
(d) Bottom floor – Refl. = 55%



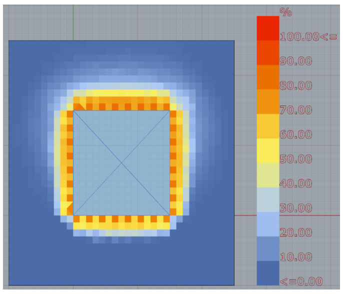
(e) Middle floor – Refl. = 55%



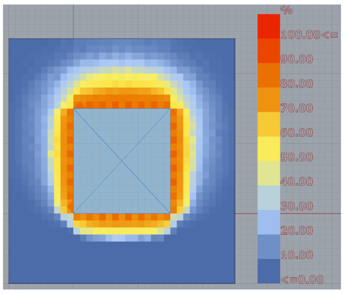
(f) Top floor – Refl. = 55%



(g) Bottom floor – Refl. = 80%



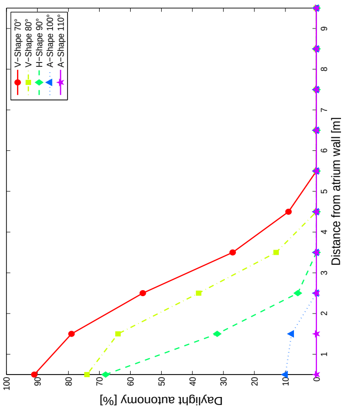
(h) Middle floor – Refl. = 80%



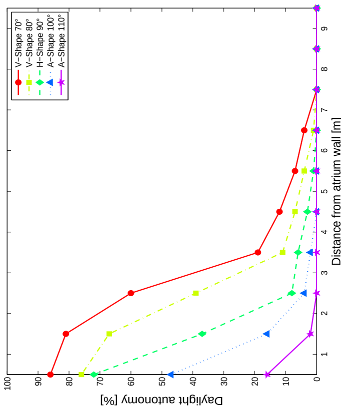
(i) Top floor – Refl. = 80%

Figure C.6: Increasing the reflectance of the atrium walls increases the daylight autonomy on the orientations that receive less direct daylight, i.e. South, East, and West. A limited increase in daylight autonomy can be noticed on the North side.

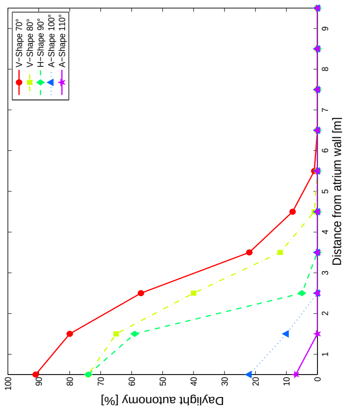
C.5 V-shape vs. A-shape



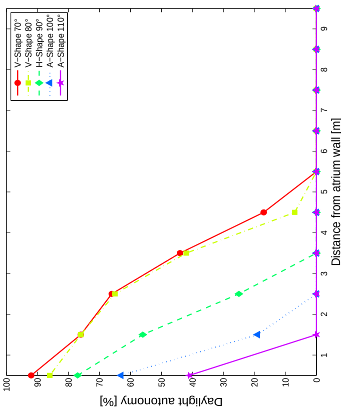
(a) Bottom floor – South



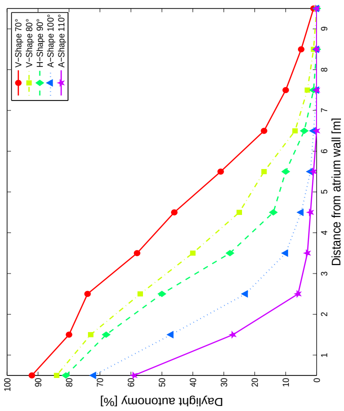
(b) Bottom floor – North



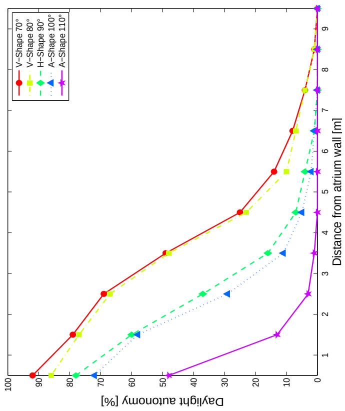
(c) Bottom floor – East



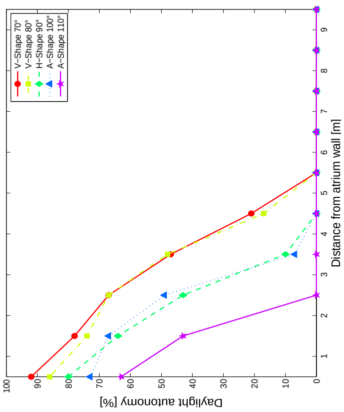
(d) Middle floor – South



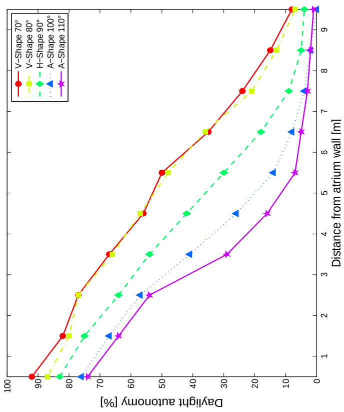
(e) Middle floor – North



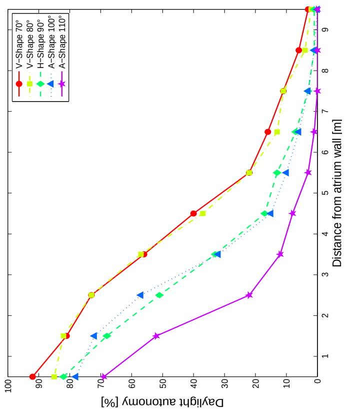
(f) Middle floor – East



(g) Top floor – South

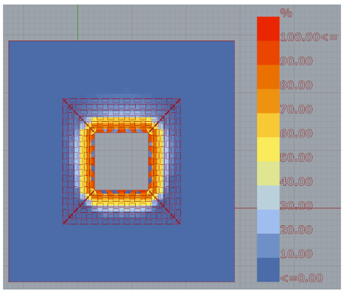


(h) Top floor – North

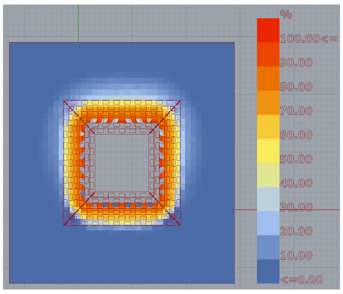


(i) Top floor – East

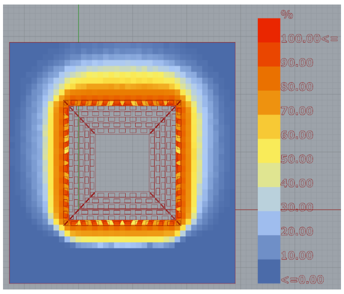
Figure C.7: Varying the slope of the atrium wall dramatically affects the daylight autonomy on all floors within the building.



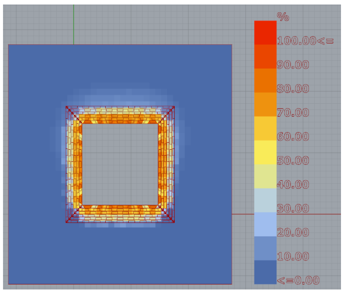
(a) Bottom floor – 70°



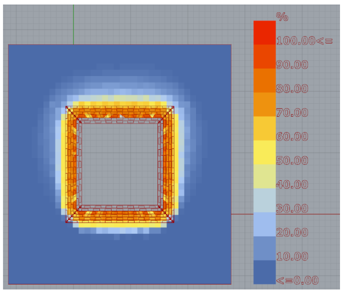
(b) Middle floor – 70°



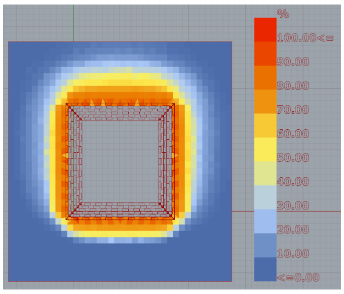
(c) Top floor – 70°



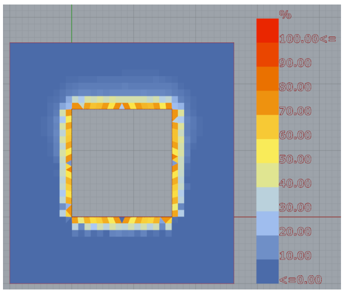
(d) Bottom floor – 80°



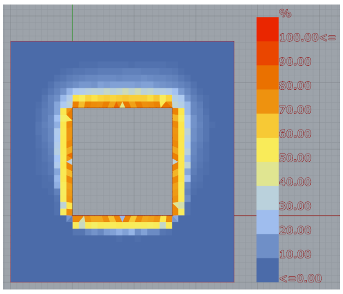
(e) Middle floor – 80°



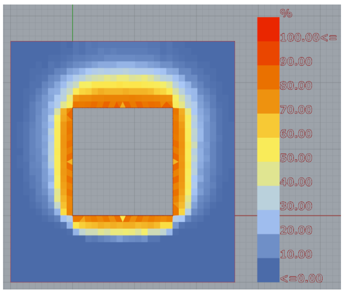
(f) Top floor – 80°



(g) Bottom floor – 90°

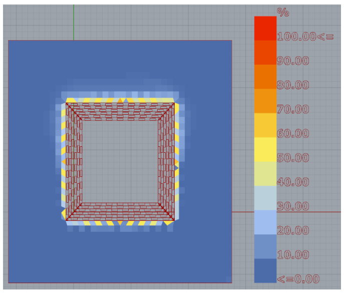


(h) Middle floor – 90°

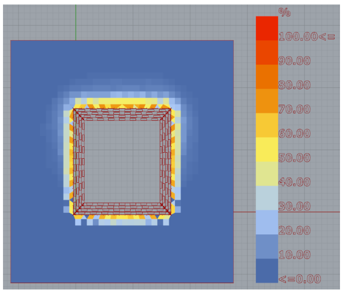


(i) Top floor – 90°

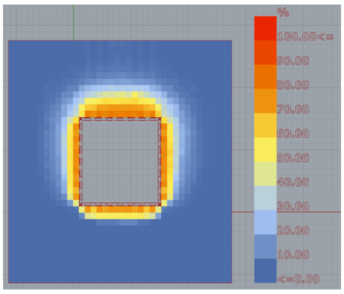
...figure continued on next page.



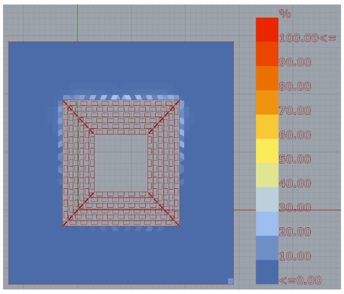
(j) Bottom floor – 100°



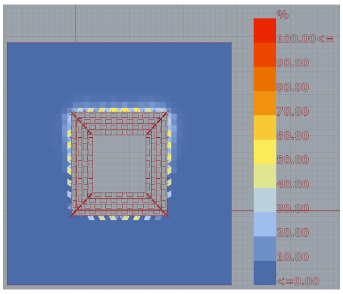
(k) Middle floor – 100°



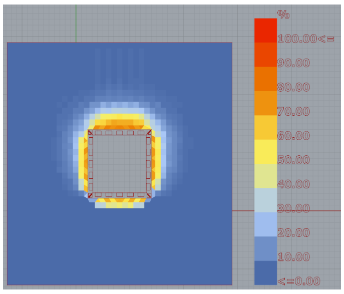
(l) Top floor – 100°



(m) Bottom floor – 110°



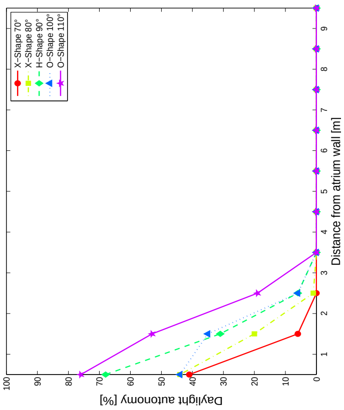
(n) Middle floor – 110°



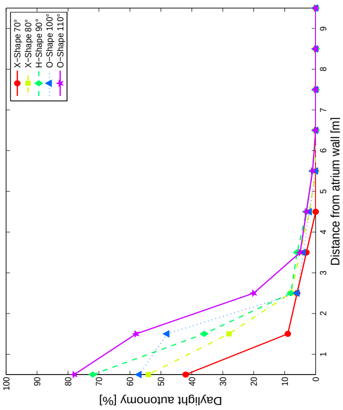
(o) Top floor – 110°

Figure C.8: Varying the slope of the atrium wall dramatically affects the daylight autonomy within the building.

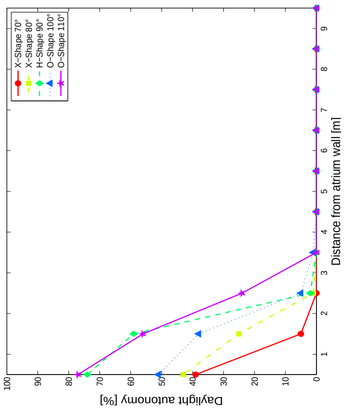
C.6 x-shape vs. ◇-shape



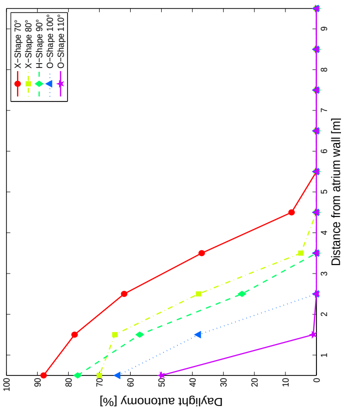
(a) Bottom floor – South



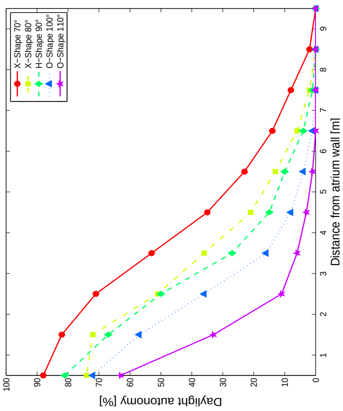
(b) Bottom floor – North



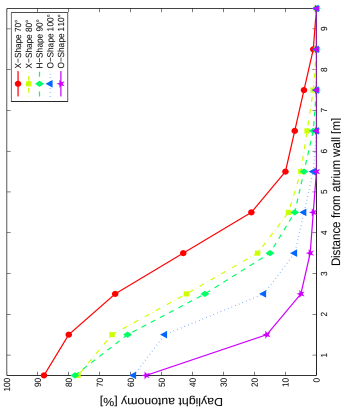
(c) Bottom floor – East



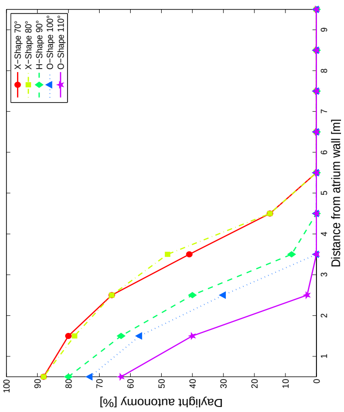
(d) Middle floor – South



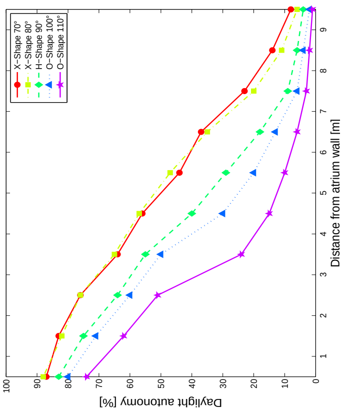
(e) Middle floor – North



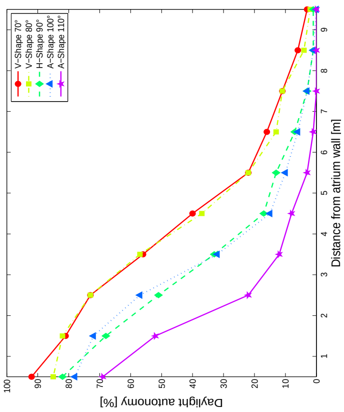
(f) Middle floor – East



(g) Top floor – South

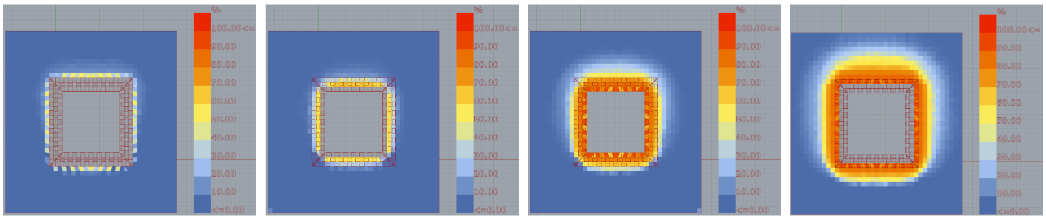


(h) Top floor – North

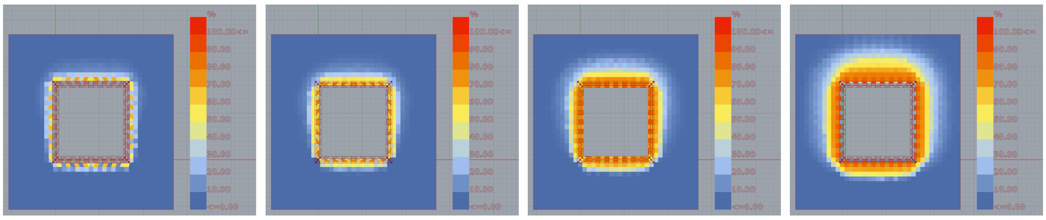


(i) Top floor – East

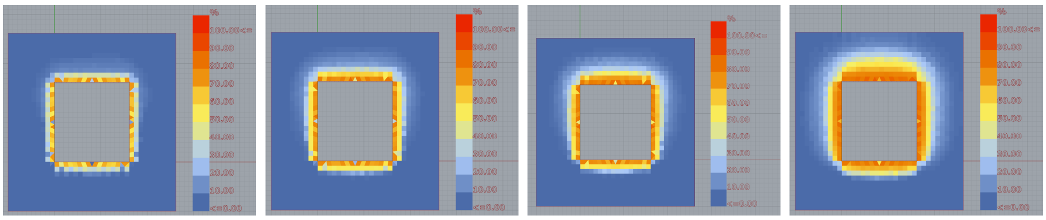
Figure C.9: Varying the slope of the atrium wall dramatically affects the daylight autonomy on all floors within the building.



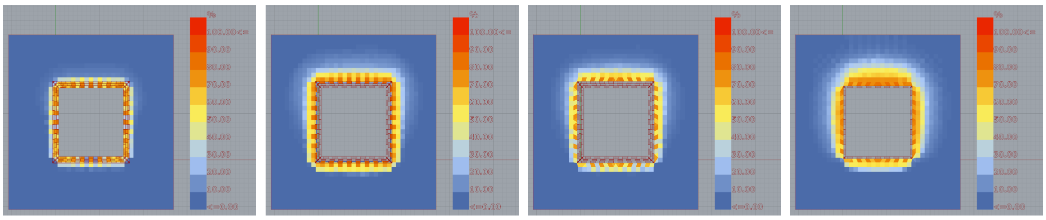
(a) Bottom floor – 70° **(b)** Middle floor (below center) – 70° **(c)** Middle floor (above center) – 70° **(d)** Top floor – 70°



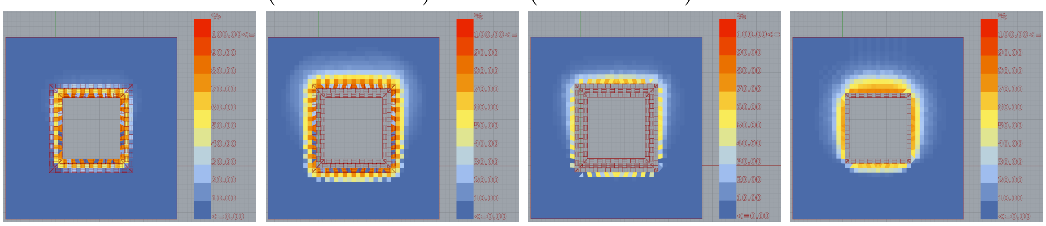
(e) Bottom floor – 80° **(f)** Middle floor (below center) – 80° **(g)** Middle floor (above center) – 80° **(h)** Top floor – 80°



(i) Bottom floor – 90° **(j)** Middle floor (below center) – 90° **(k)** Middle floor (above center) – 90° **(l)** Top floor – 90°



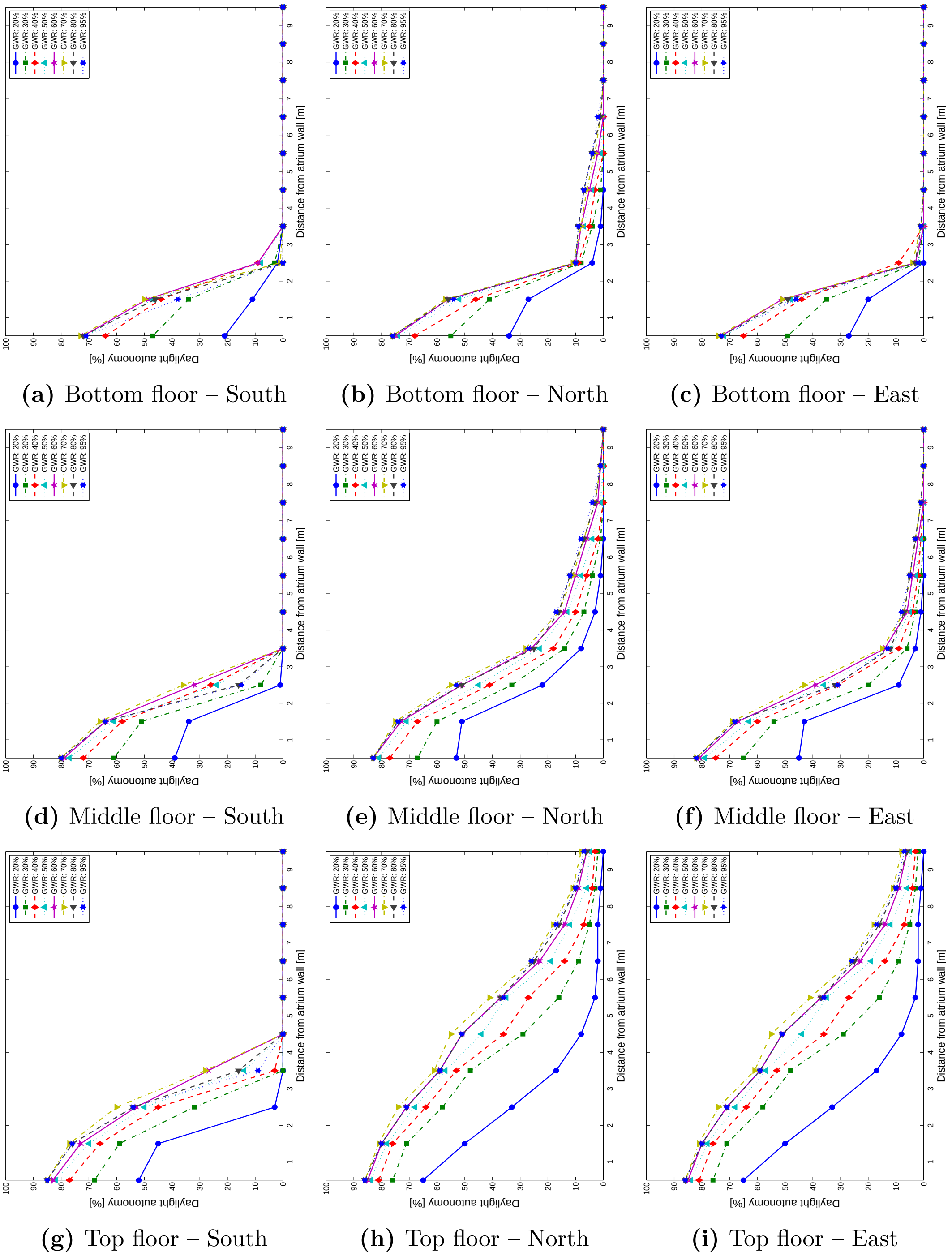
(m) Bottom floor – 100° **(n)** Middle floor (below center) – 100° **(o)** Middle floor (above center) – 100° **(p)** Top floor – 100°



(q) Bottom floor – 110° **(r)** Middle floor (below center) – 110° **(s)** Middle floor (above center) – 110° **(t)** Top floor – 110°

Figure C.10: Varying the slope of the atrium wall dramatically affects the daylight autonomy within the building.

C.7 Glazing convergence

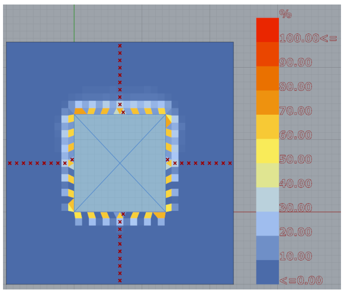


(a) Bottom floor – South **(b)** Bottom floor – North **(c)** Bottom floor – East

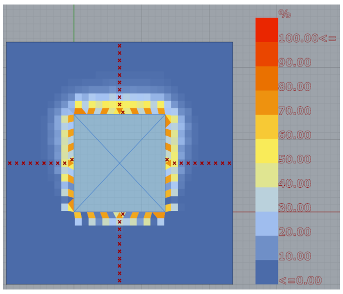
(d) Middle floor – South **(e)** Middle floor – North **(f)** Middle floor – East

(g) Top floor – South **(h)** Top floor – North **(i)** Top floor – East

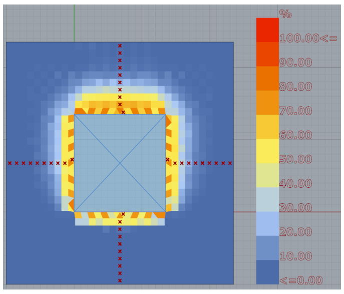
Figure C.11: The resulting daylight autonomy studied for increasing the glazing-to-wall ratio



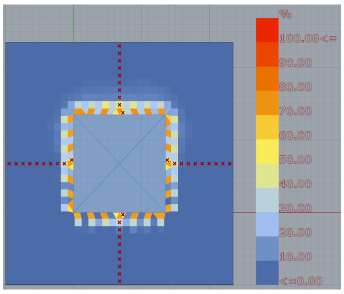
(a) Bottom floor – GWR = 20%



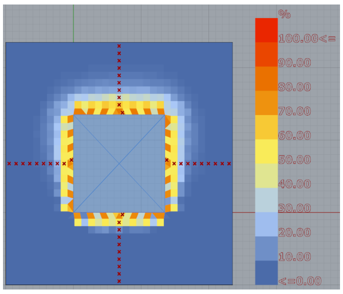
(b) Middle floor –GWR = 20%



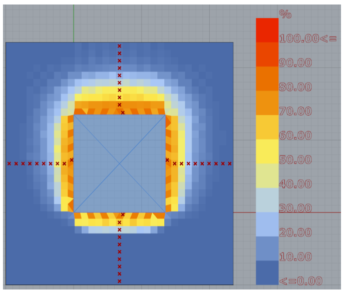
(c) Top floor – GWR = 20%



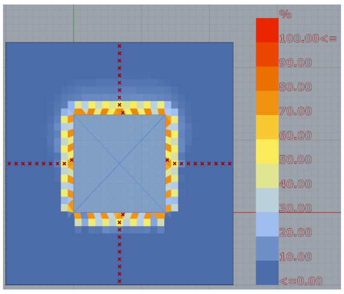
(d) Bottom floor – GWR = 30%



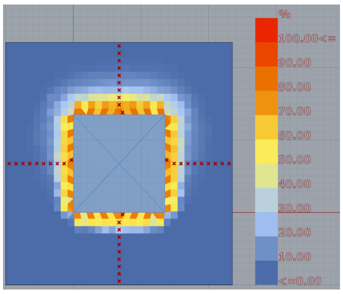
(e) Middle floor – GWR = 30%



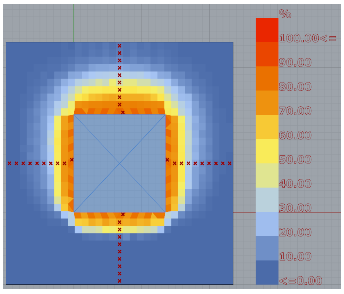
(f) Top floor – GWR = 30%



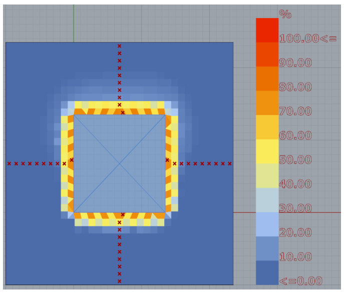
(g) Bottom floor – GWR = 40%



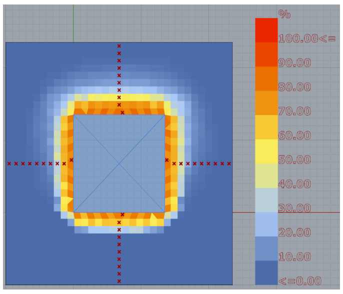
(h) Middle floor – GWR = 40%



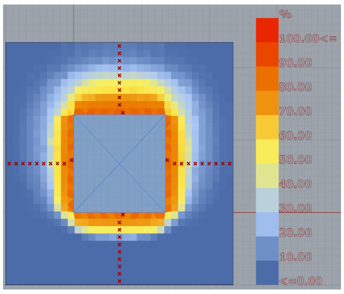
(i) Top floor – GWR = 40%



(j) Bottom floor – GWR = 50%

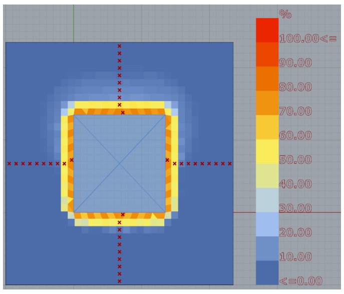


(k) Middle floor – GWR = 50%

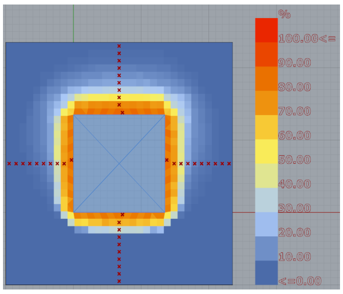


(l) Top floor – GWR = 50%

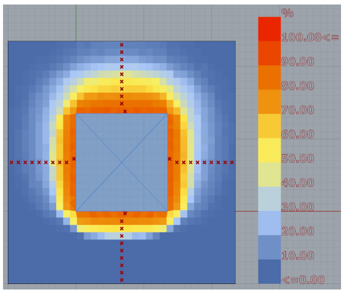
...figure continued on next page.



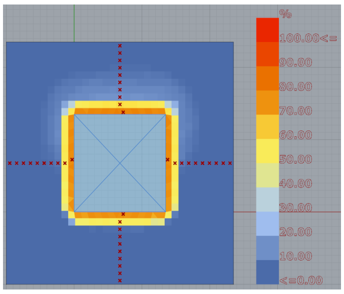
(m) Bottom floor – GWR = 60%



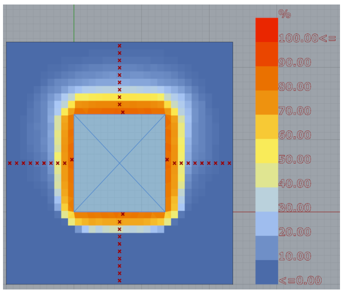
(n) Middle floor – GWR = 60%



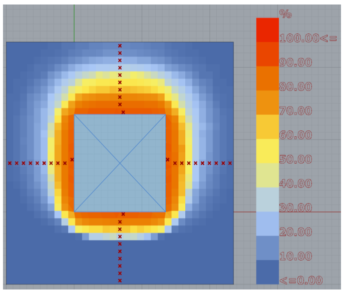
(o) Top floor – GWR = 60%



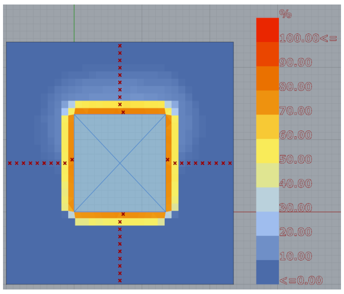
(p) Bottom floor – GWR = 70%



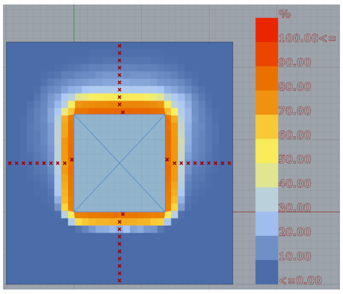
(q) Middle floor – GWR = 70%



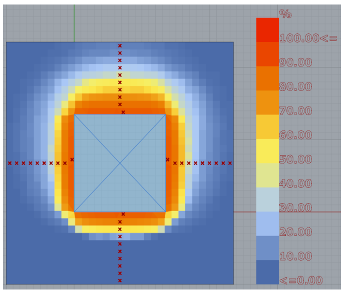
(r) Top floor – GWR = 70%



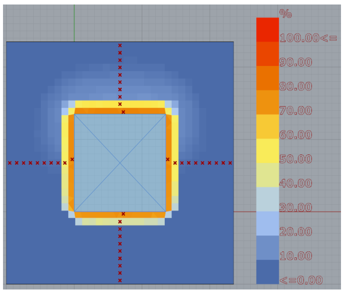
(s) Bottom floor – GWR = 80%



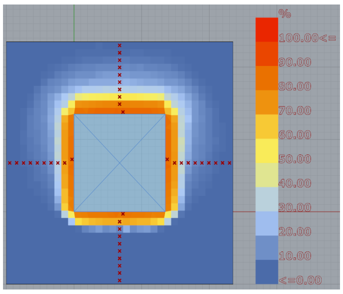
(t) Middle floor – GWR = 80%



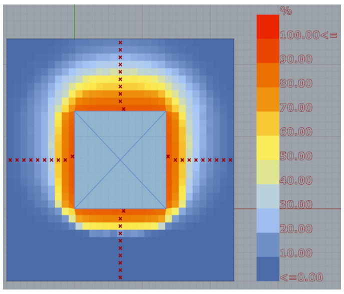
(u) Top floor – GWR = 80%



(v) Bottom floor – GWR = 95%



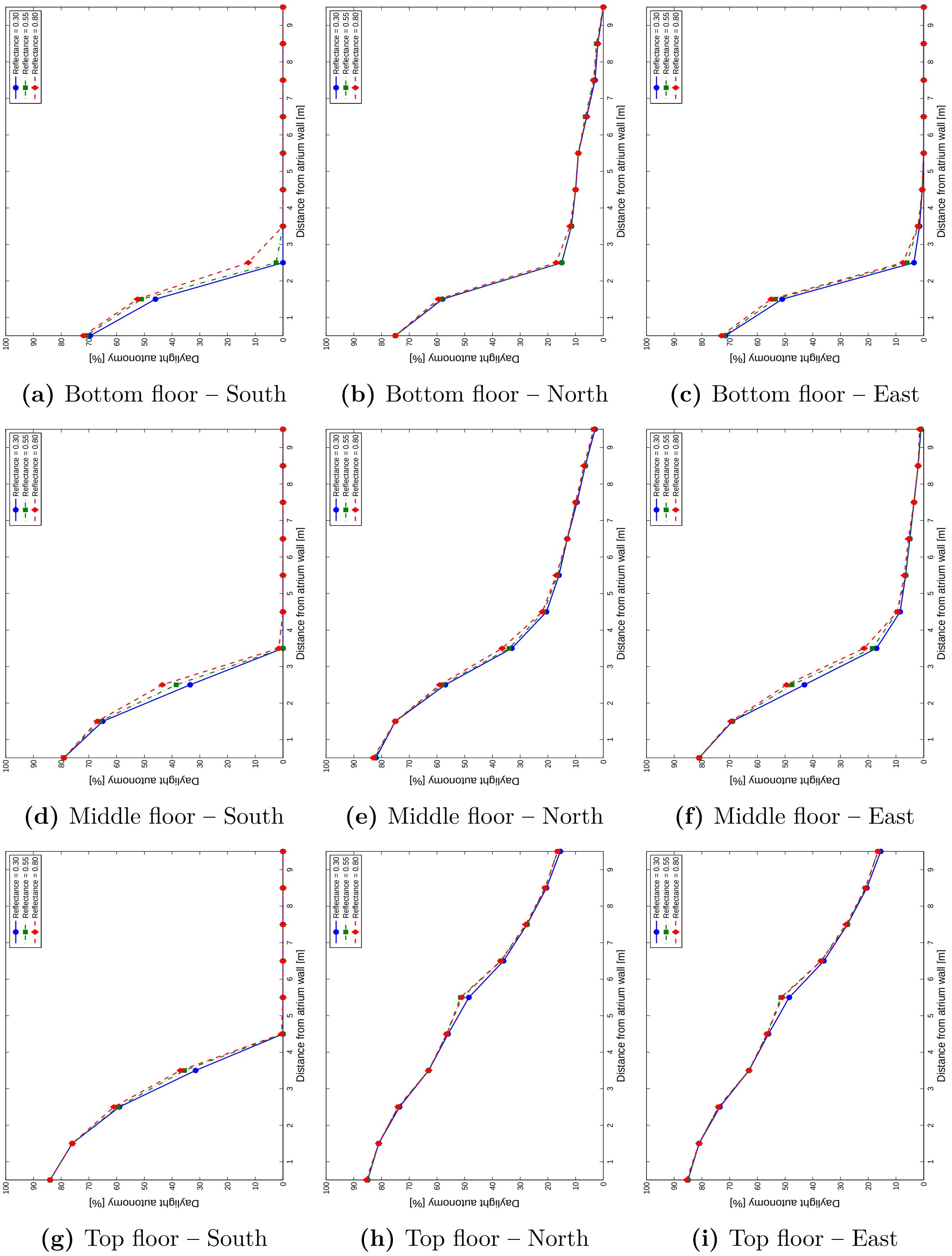
(w) Middle floor – GWR = 95%



(x) Top floor – GWR = 95%

Figure C.12: The resulting daylight autonomy for increasing the glazing-to-wall ratio.

C.7.1 Reflectance of surfaces in an atrium with GWR = 70%



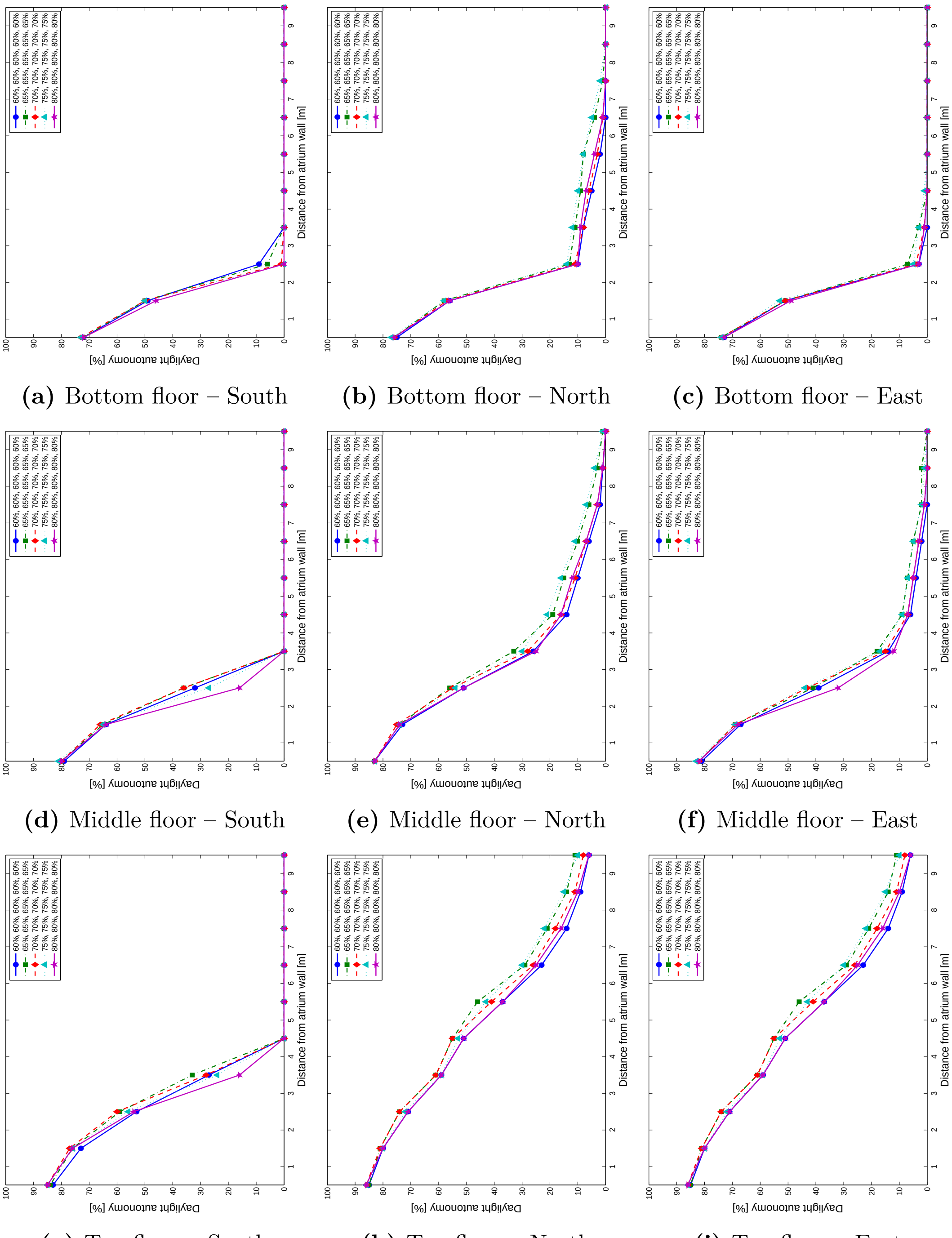
(a) Bottom floor – South **(b)** Bottom floor – North **(c)** Bottom floor – East

(d) Middle floor – South **(e)** Middle floor – North **(f)** Middle floor – East

(g) Top floor – South **(h)** Top floor – North **(i)** Top floor – East

Figure C.13: Even with high GWR, the reflectance of atrium walls has a slight impact.

C.7.2 GWR value optimized



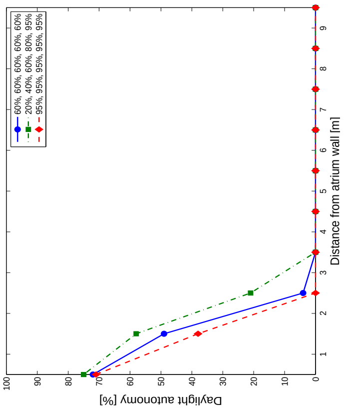
(a) Bottom floor – South **(b)** Bottom floor – North **(c)** Bottom floor – East

(d) Middle floor – South **(e)** Middle floor – North **(f)** Middle floor – East

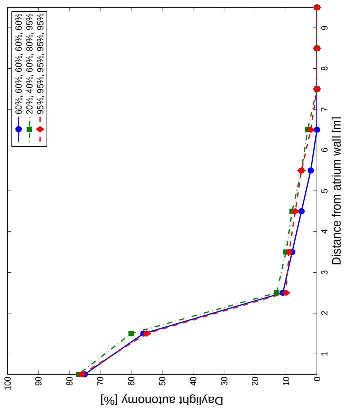
(g) Top floor – South **(h)** Top floor – North **(i)** Top floor – East

Figure C.14: The daylight autonomy reaches a maximum at GWR = 60–65%

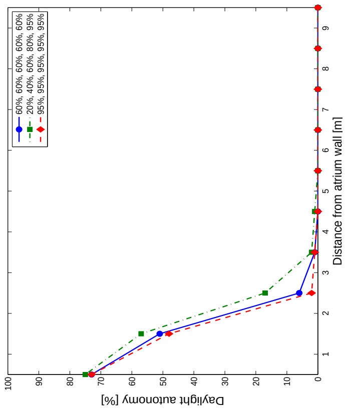
C.8 Varying GWR between floors



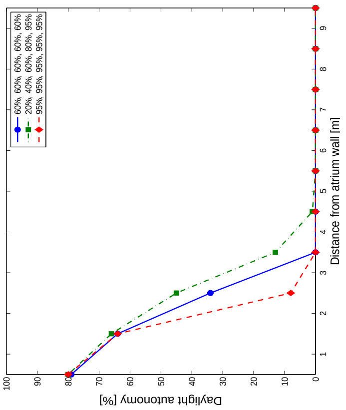
(a) Bottom floor – South



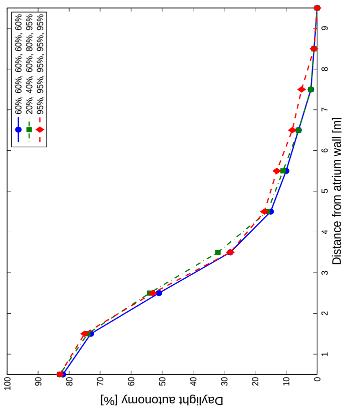
(b) Bottom floor – North



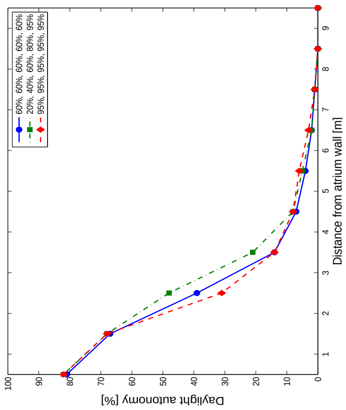
(c) Bottom floor – East



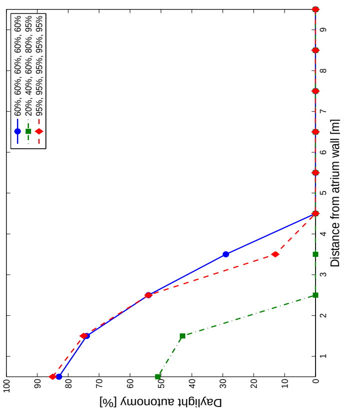
(d) Middle floor – South



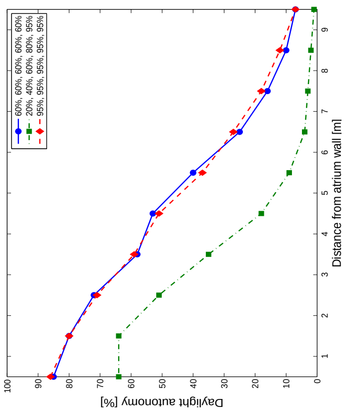
(e) Middle floor – North



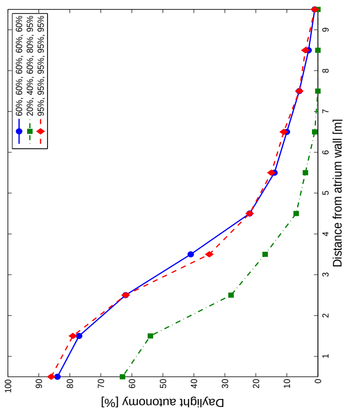
(f) Middle floor – East



(g) Top floor – South



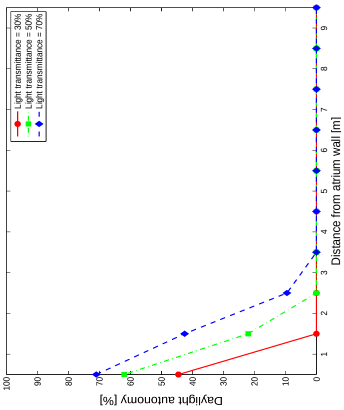
(h) Top floor – North



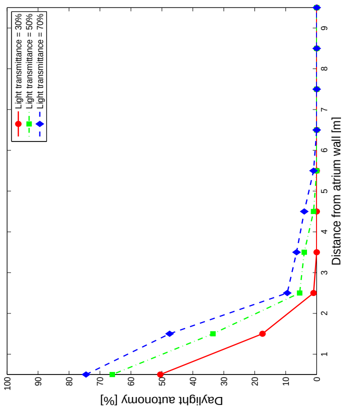
(i) Top floor – East

Figure C.15: Varying the glazing within an atrium will result in increased daylight autonomy due to the reflected component of the light within the atrium. (See figure C.12 for DA distribution)

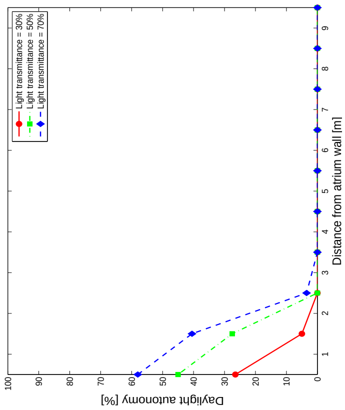
C.9 Light transmittance of glazing



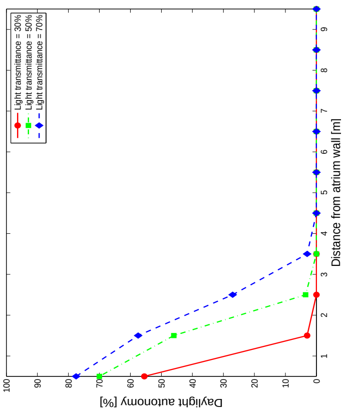
(a) Bottom floor – South



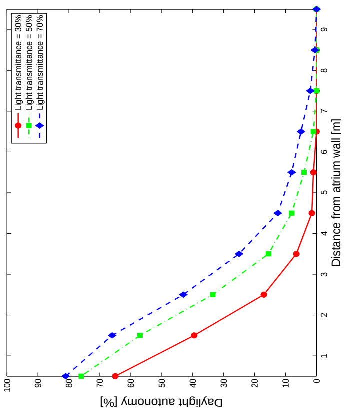
(b) Bottom floor – North



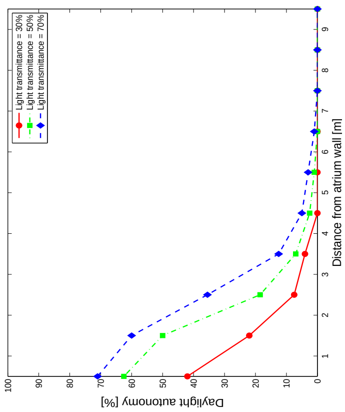
(c) Bottom floor – East



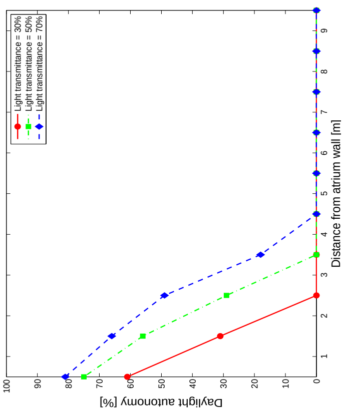
(d) Middle floor – South



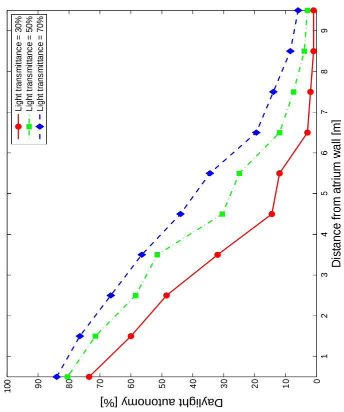
(e) Middle floor – North



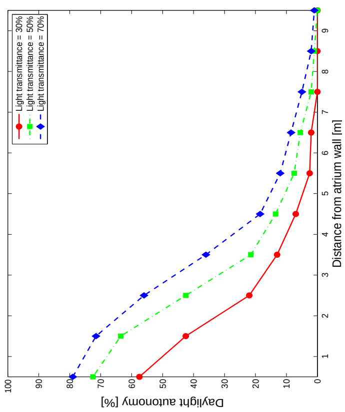
(f) Middle floor – East



(g) Top floor – South

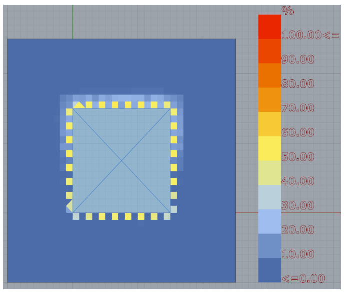


(h) Top floor – North

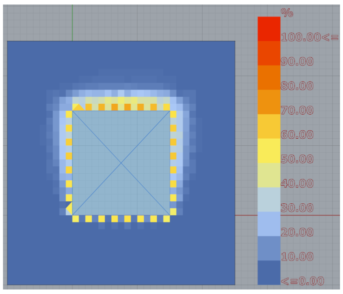


(i) Top floor – East

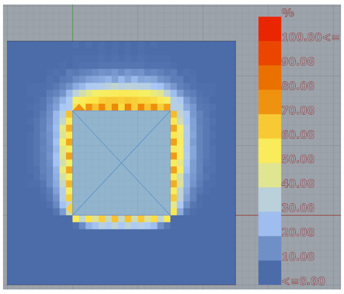
Figure C.16: Daylight autonomy for different light transmittance of atrium windows.



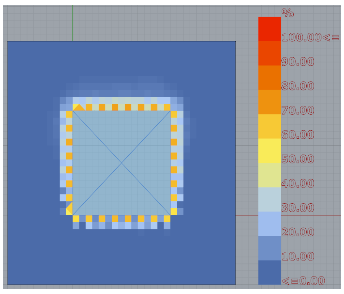
(a) Bottom floor – LT = 30%



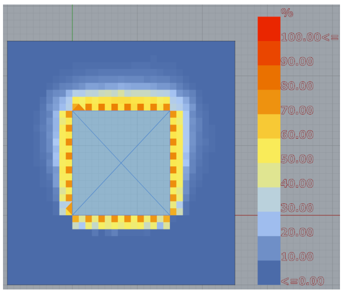
(b) Middle floor – LT = 30%



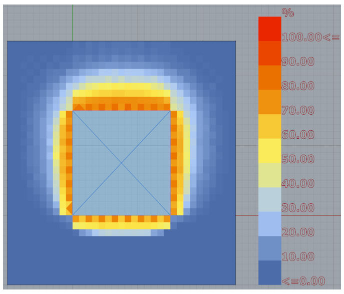
(c) Top floor – LT = 30%



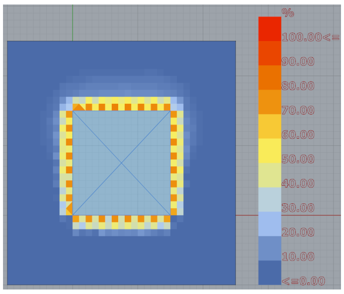
(d) Bottom floor – LT = 50%



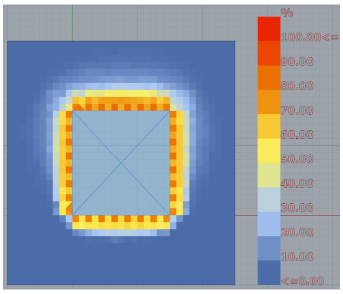
(e) Middle floor – LT = 50%



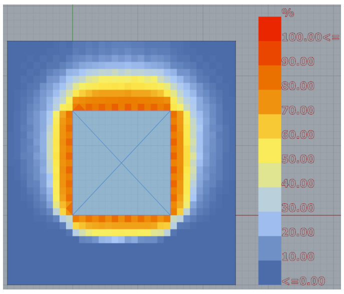
(f) Top floor – LT = 50%



(g) Bottom floor – LT = 70%



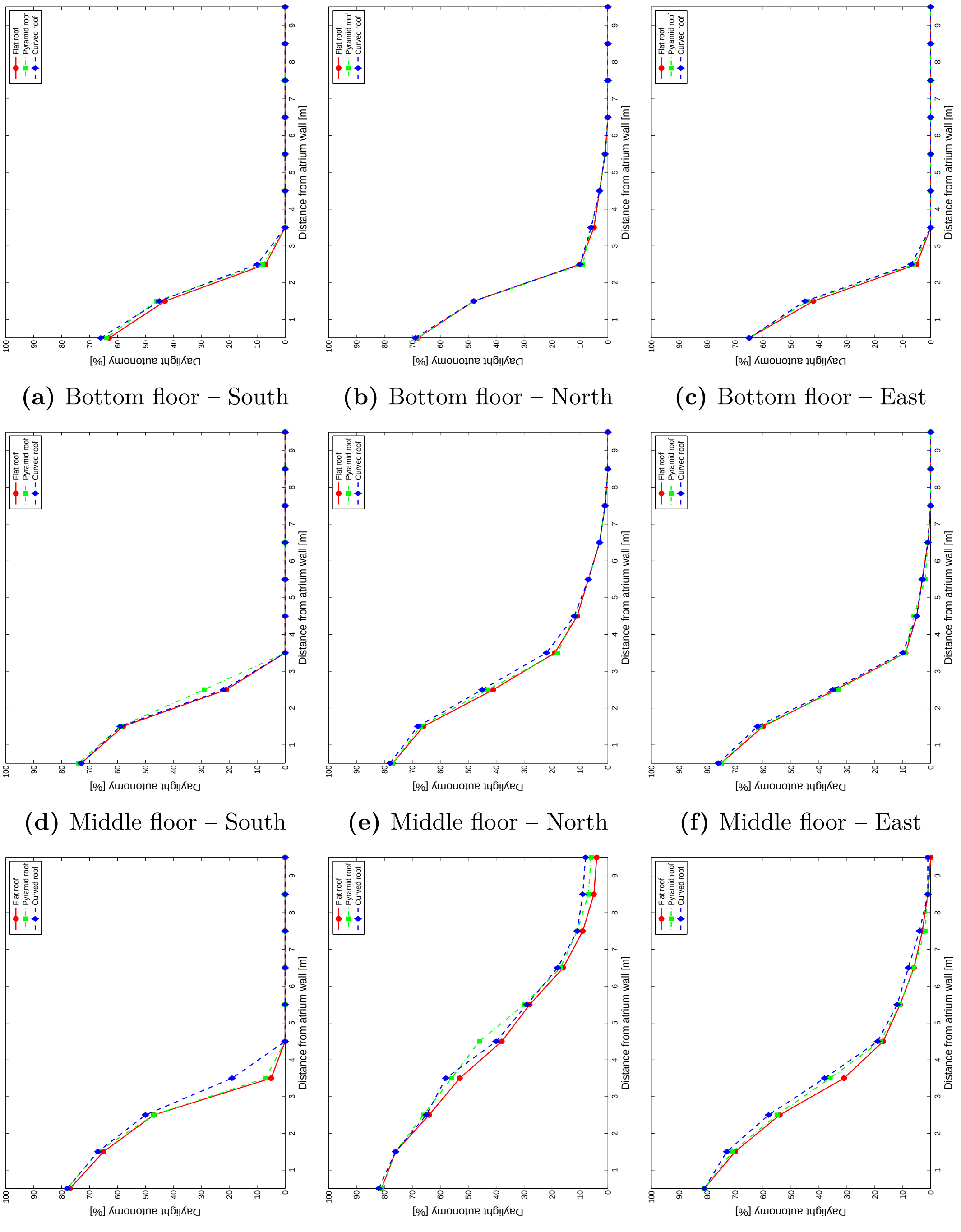
(h) Middle floor – LT = 70%



(i) Top floor – LT = 70%

Figure C.17: Daylight autonomy for different light transmittance of atrium windows.

C.10 Shape of atrium roof glazing



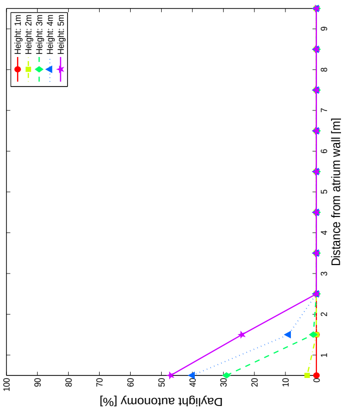
(a) Bottom floor – South **(b)** Bottom floor – North **(c)** Bottom floor – East

(d) Middle floor – South **(e)** Middle floor – North **(f)** Middle floor – East

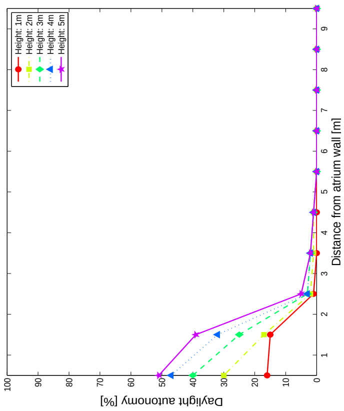
(g) Top floor – South **(h)** Top floor – North **(i)** Top floor – East

Figure C.18: The shape of the atrium roof glazing has negligible effect on the daylight autonomy.

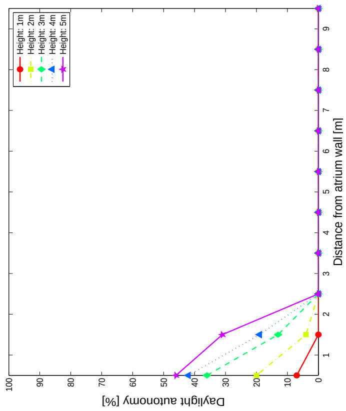
C.11 Height of four sided atrium (box)



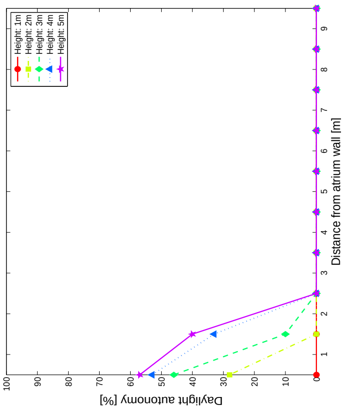
(a) Bottom floor – South



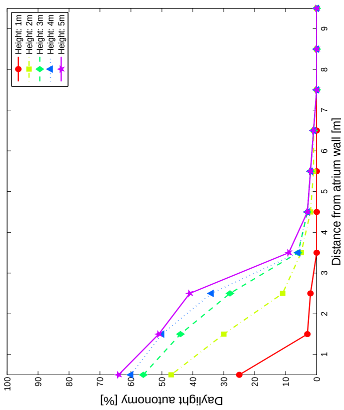
(b) Bottom floor – North



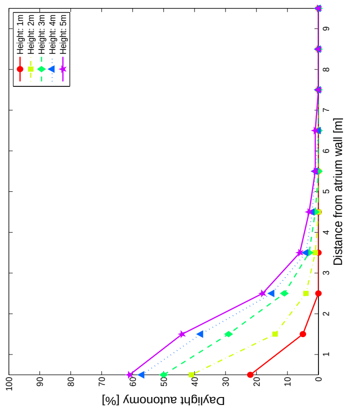
(c) Bottom floor – East



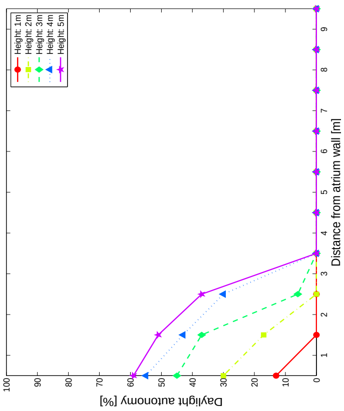
(d) Middle floor – South



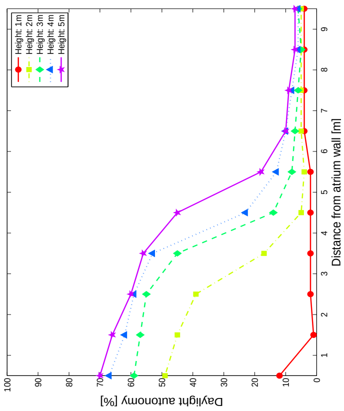
(e) Middle floor – North



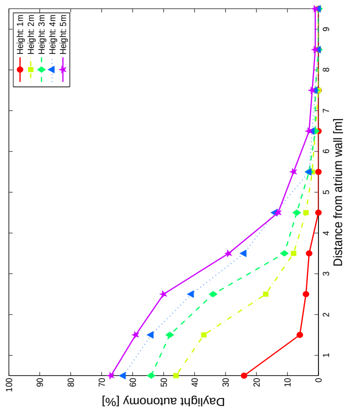
(f) Middle floor – East



(g) Top floor – South

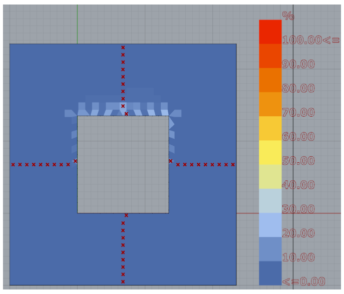


(h) Top floor – North

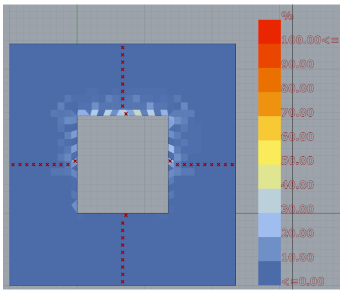


(i) Top floor – East

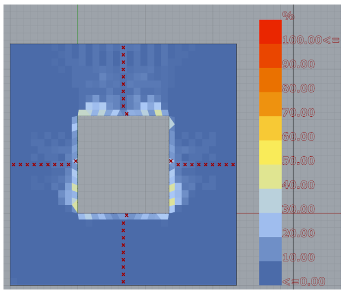
Figure C.19: Increasing the height of the box increases the access to daylight and thus increases the daylight distribution within the building. A box-heights greater than the average floor-to-floor height within the building is however unlikely.



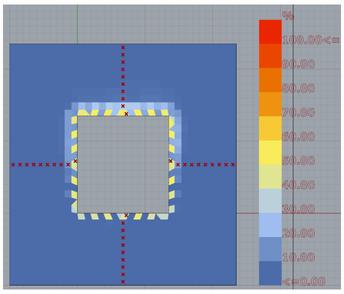
(a) Bottom floor – Height = 1 m



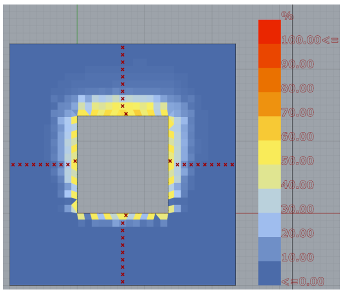
(b) Middle floor –Height = 1 m



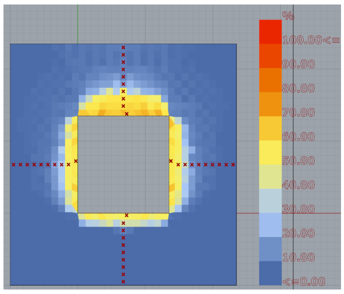
(c) Top floor – Height = 1 m



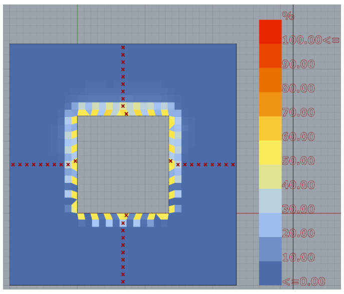
(d) Bottom floor – Height = 3 m



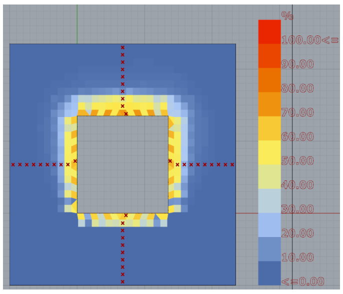
(e) Middle floor – Height = 3 m



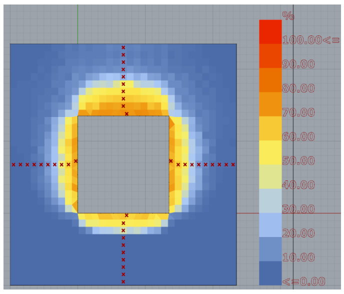
(f) Top floor – Height = 3 m



(g) Bottom floor – Height = 5 m



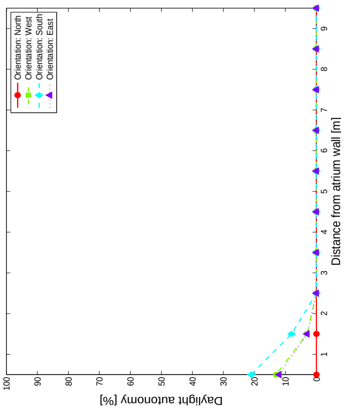
(h) Middle floor – Height = 5 m



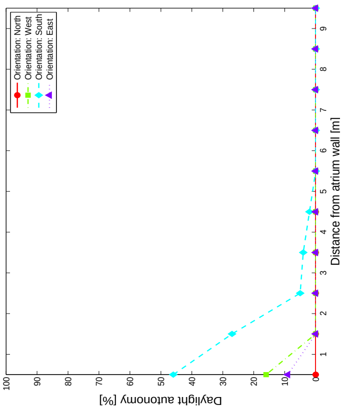
(i) Top floor – Height = 5 m

Figure C.20: Increasing the height of the box increases the access to daylight and thus increases the daylight distribution within the building. A box-heights greater than the average floor-to-floor height within the building is however unlikely.

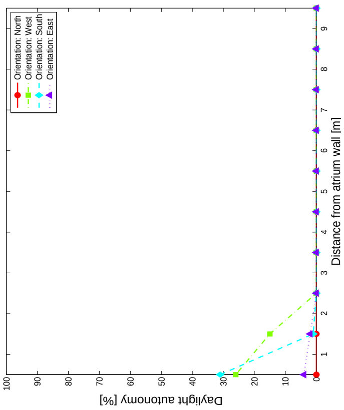
C.12 Sawtooth orientation



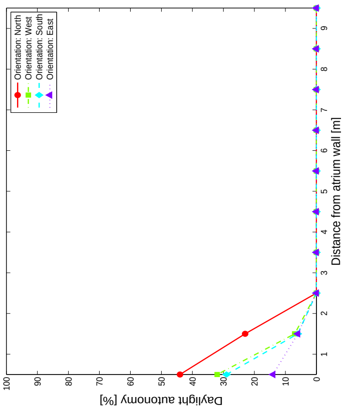
(a) Bottom floor – South



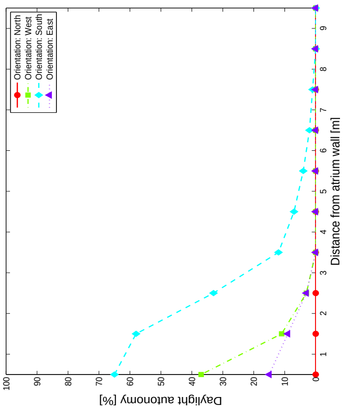
(b) Bottom floor – North



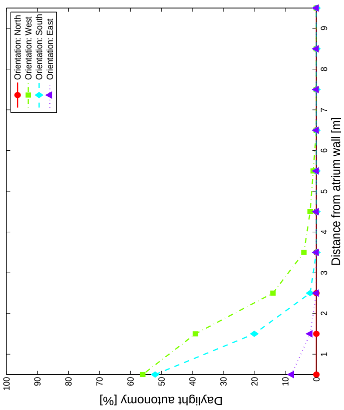
(c) Bottom floor – East



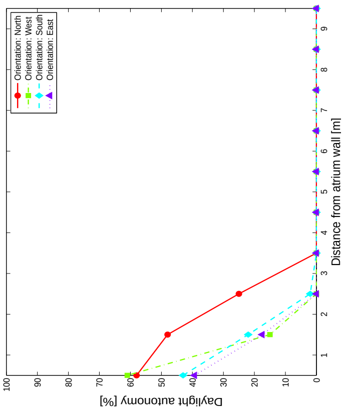
(d) Middle floor – South



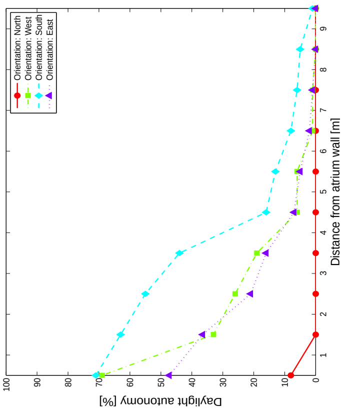
(e) Middle floor – North



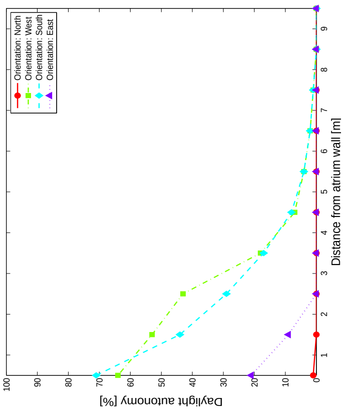
(f) Middle floor – East



(g) Top floor – South



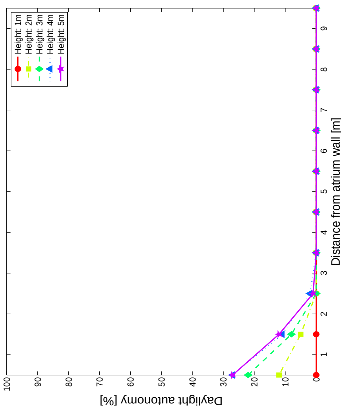
(h) Top floor – North



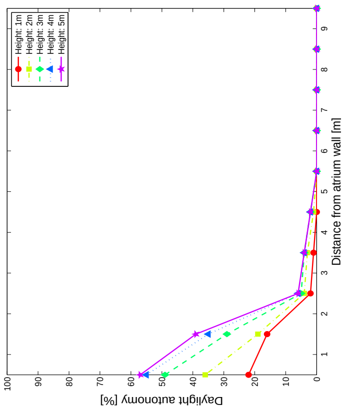
(i) Top floor – East

Figure C.21: The sawtooth roof only offers access to natural light on the opposing floor plan of the sawtooth orientation.

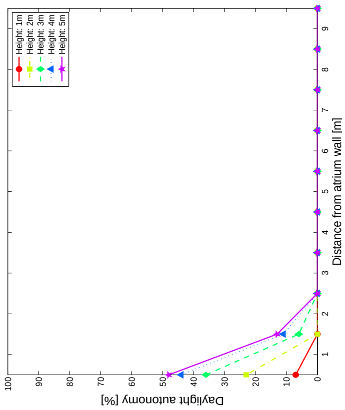
C.13 Sawtooth height



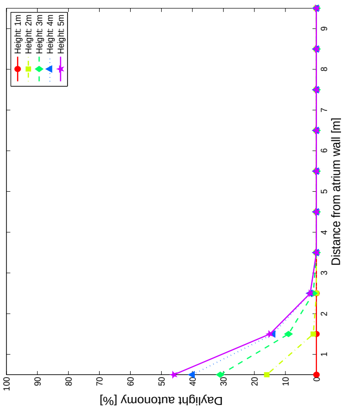
(a) Bottom floor – South



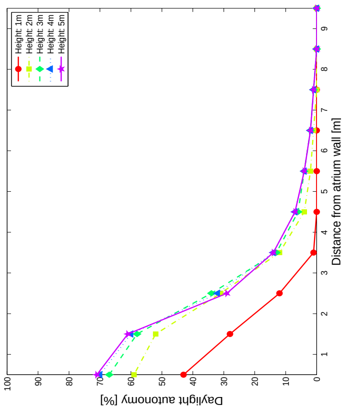
(b) Bottom floor – North



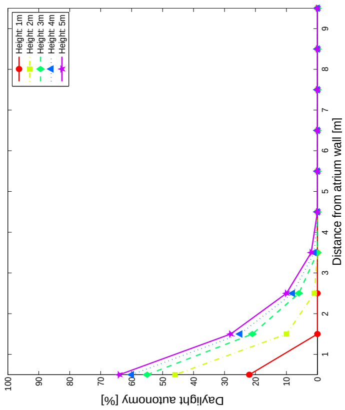
(c) Bottom floor – East



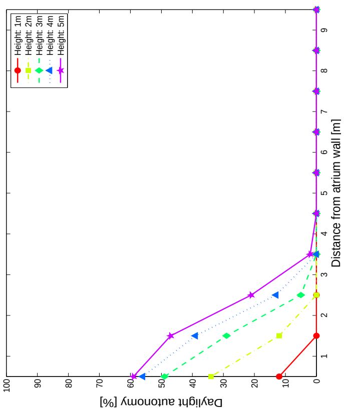
(d) Middle floor – South



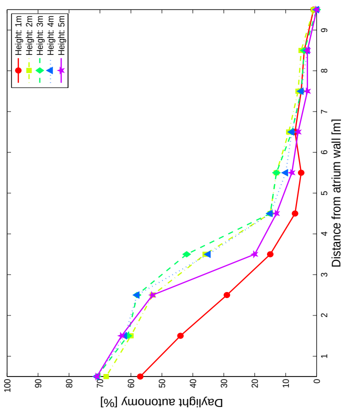
(e) Middle floor – North



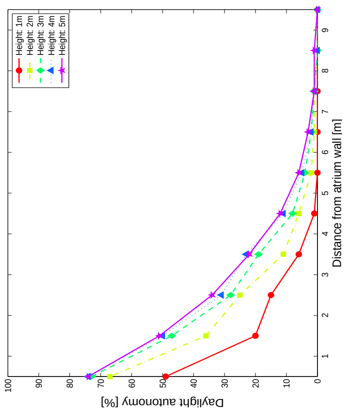
(f) Middle floor – East



(g) Top floor – South

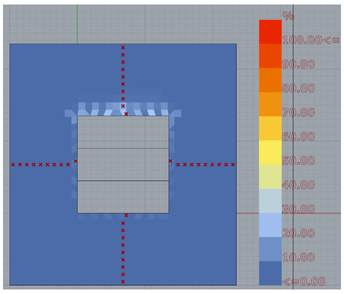


(h) Top floor – North

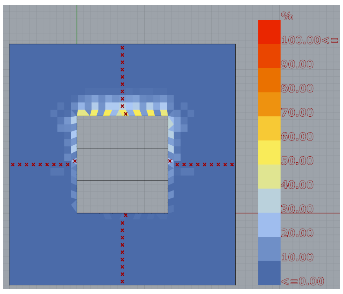


(i) Top floor – East

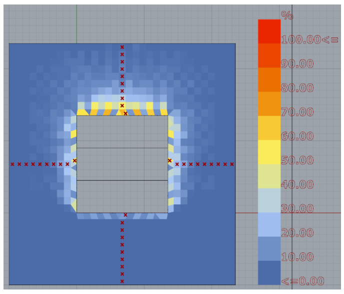
Figure C.22: Increasing the height of the sawtooth roof increases the access to daylight and thus increases the daylight autonomy within the building, mostly on the opposite floor plan to the sawtooth orientation. A roof-height greater than the average floor-to-floor height within the building is however unlikely.



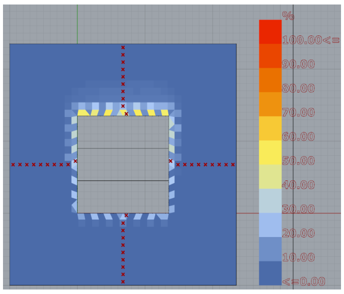
(a) Bottom floor – Height = 1 m



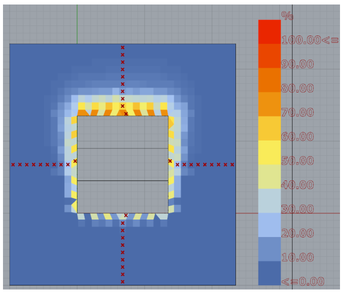
(b) Middle floor –Height = 1 m



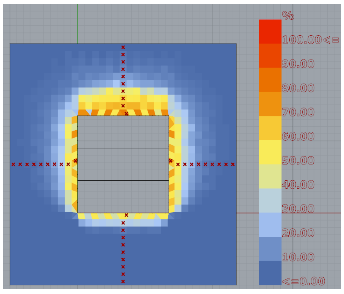
(c) Top floor – Height = 1 m



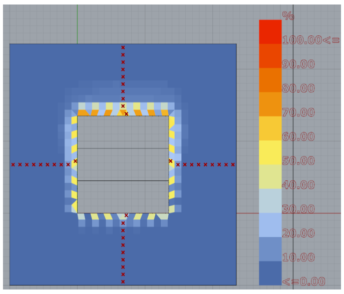
(d) Bottom floor – Height = 3 m



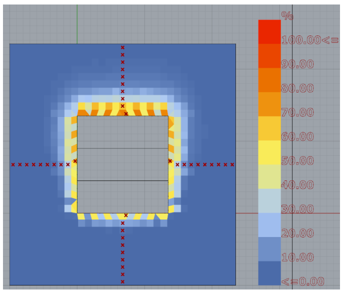
(e) Middle floor – Height = 3 m



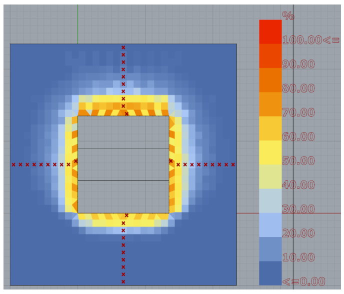
(f) Top floor – Height = 3 m



(g) Bottom floor – Height = 5 m



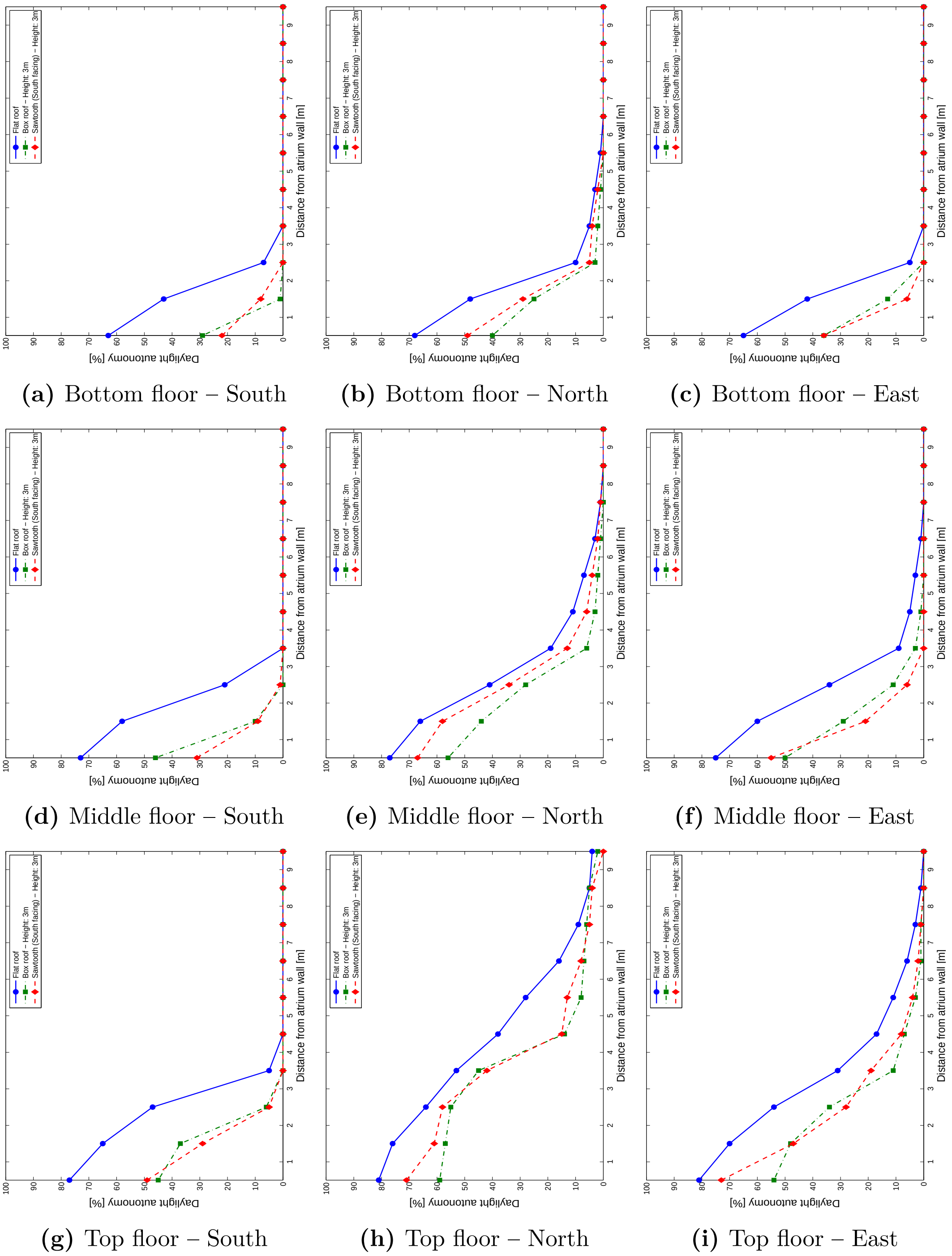
(h) Middle floor – Height = 5 m



(i) Top floor – Height = 5 m

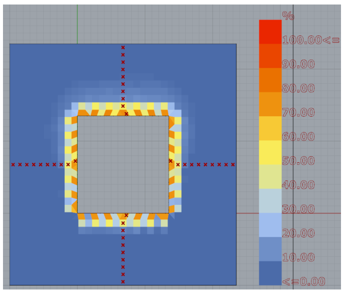
Figure C.23: Increasing the height of the sawtooth roof increases the access to daylight and thus increases the daylight autonomy within the building, mostly on the opposite floor plan to the sawtooth orientation. A roof-height greater than the average floor-to-floor height within the building is however unlikely.

C.14 Comparing different atrium roof types

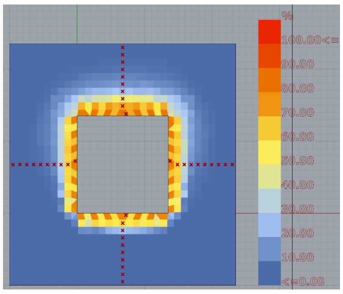


(a) Bottom floor – South
(b) Bottom floor – North
(c) Bottom floor – East
(d) Middle floor – South
(e) Middle floor – North
(f) Middle floor – East
(g) Top floor – South
(h) Top floor – North
(i) Top floor – East

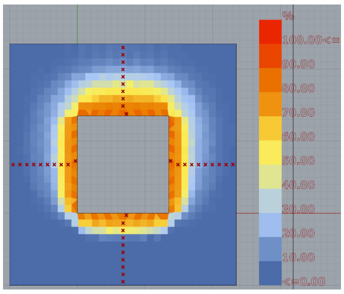
Figure C.24: The different roof types studied (flat, pyramid, curved, box, and sawtooth).



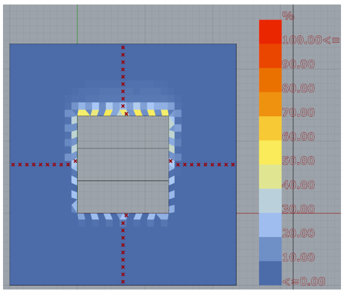
(a) Bottom floor – Flat roof



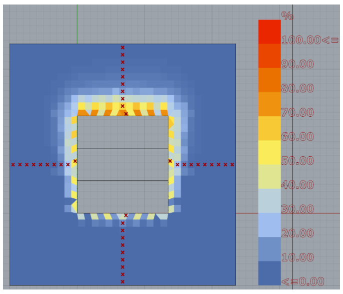
(b) Middle floor – Flat roof



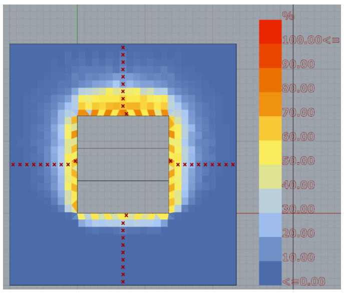
(c) Top floor – Flat roof



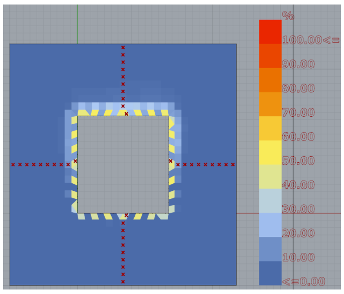
(d) Bottom floor – Sawtooth roof



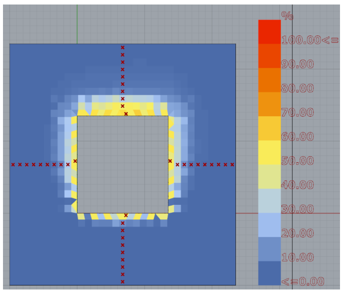
(e) Middle floor – Sawtooth roof



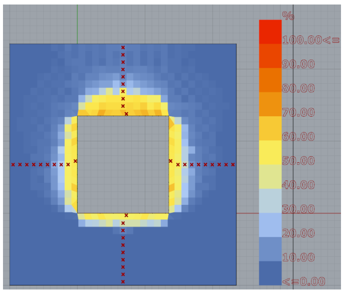
(f) Top floor – Sawtooth roof



(g) Bottom floor – Box roof



(h) Middle floor – Box roof



(i) Top floor – Box roof

Figure C.25: The different roof types studied (flat, pyramid, curved, box, and sawtooth).

Appendix D

An example of the contents of the guideline document

Atria - Early Stage Design Guidelines for daylight optimisation

ATRIUM SLOPE: V-SHAPE & A-SHAPE

CONTEXT

Study question: ***How does the slope of the atrium wall effect the daylight distribution and which shape gives the best result?***

Simulation parameters: Wall slope (70, 80, 90, 100, 110)

Note: For the purpose of this study, all walls were sloped simlutaneously so that the atrium was either narrower at the top than at the base, or the opposite. The two variations were then compared to the standard 90° angle atrium. Hence, three shapes were studied, V-shape , H-shape, (standard) and A-shape. The atrium volume was kept constant so that the same amount of exploitable floor area was studied for each shape and wall slope.

Result interpretation: For all orientations studied, increasing the angle of the walls (thus making the atrium narrower at the top than at the bottom) results in less access to daylight, and consequently less daylight autonomy on the builging's floor plans. Litle or no decrease in DA occurs for the first 10 degree increase at the upper-most levels, but the DA becomes noticably poorer at the lower levels.

Making the atrium wider at the top than at its base has significant effect on all floors as it allows for more access to daylight. Decreasing the angle from 80 to 70 degrees does however only show significant effect on the bottom floors.

Conclusion: ***Making an atrium wider at its top than at its base will increase daylight distribution on all floor plans.***

Geometry:
- Plan depth: 10 m
- Floor-to-ceiling height: 3 m
- Atrium GWR: 40%
- Atrium roof type: Flat, glazed
- Analysis grid size: 1.0 x 1.0 m

Input data:
- Wall reflectance: 0.8
- Ceiling reflectance: 0.9
- Floor reflectance: 0.5
- Light transmittance of glazing: 0.7
- Sky condition: annual EPW weather file for Stockholm

Output: Daylight autonomy at the bottom-, middle-, and top-floor of each building, along a center line reaching from the atrium wall towards the facade.

Figure D.1: Colour coding is used to highlight the question (in red) and the conclusion (in green) from the detailed analysis (in black). This makes the document more accessible for those that need quick answers.

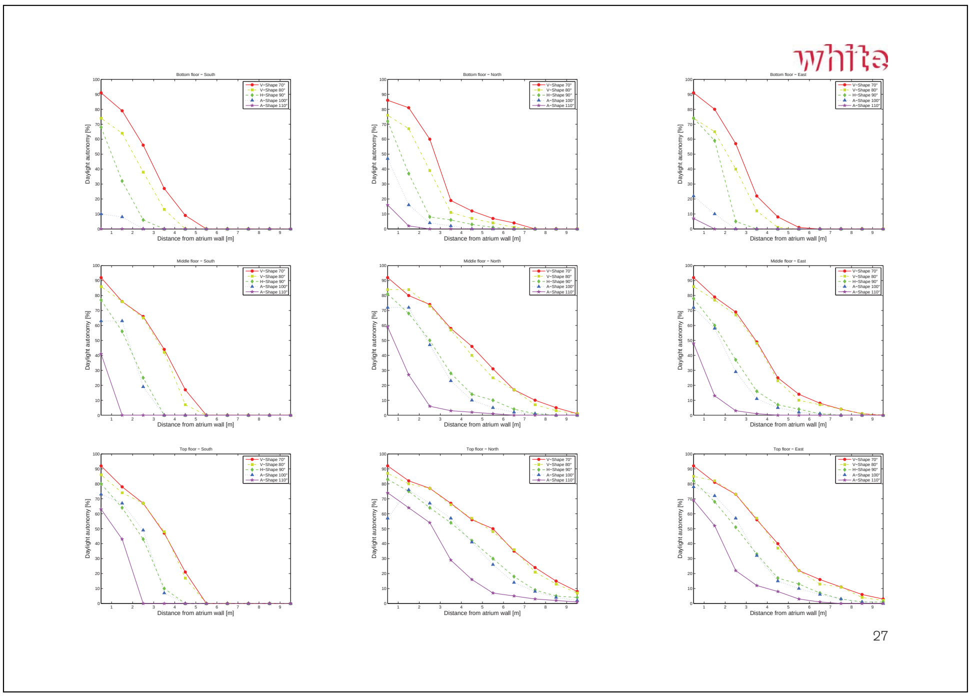


Figure D.2: A technical comparison is presented of the parameter in question. The plots show the resulting daylight autonomy along a center-line reaching from the atrium wall towards the façade for the South, North, and East orientation.

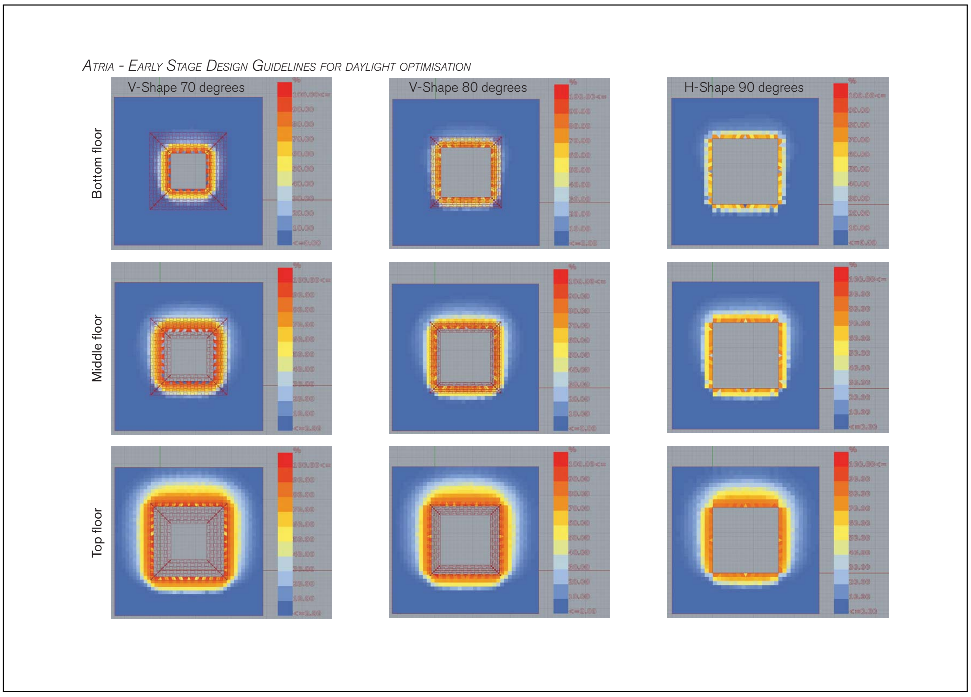


Figure D.3: For a more graphical result presentation, the daylight autonomy is given on the most interesting floors within the building model.

Appendix E

The Rhino and Grasshopper interfaces

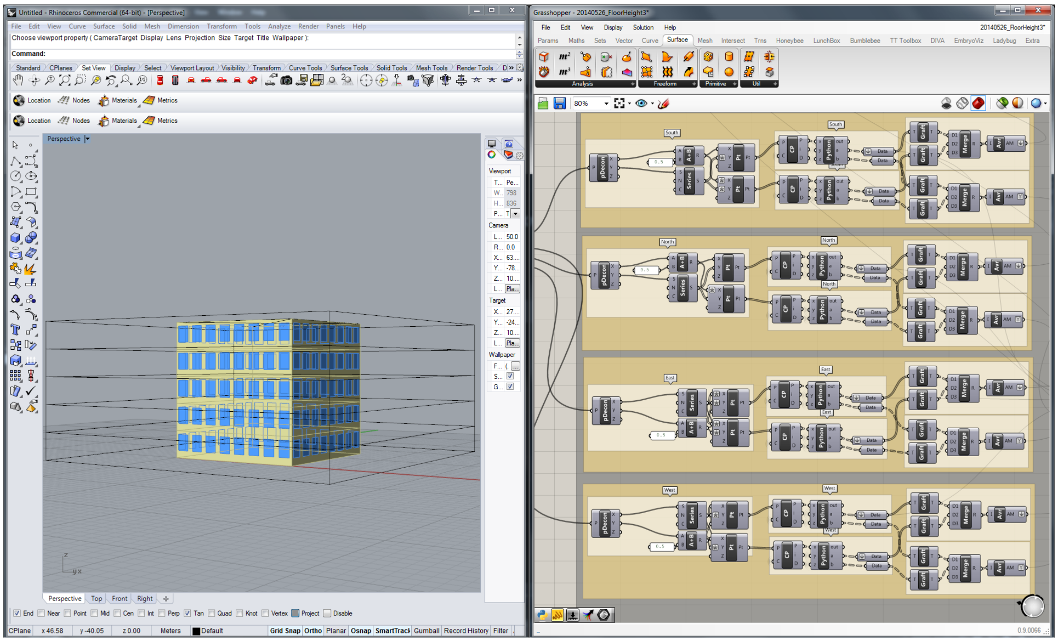


Figure E.1: The Grasshopper environment (right) opens as an extension to Rhino (left). Changes made in Grasshopper are directly represented in the Rhino window.

Appendix F

Recommended reading

S. Darula and R. Kittler. CIE general sky standard defining luminance distributions. Technical report, Institue of Construction and Architecture, Slovak Academy of Sciences, 2001.

L. Edwards and P. Torcellini. *A Literature Review of the Effects of Natural Light on Building Occupants*. U.S. Department of Energy Laboratory. Technical report. July, 2002.

A. Jacobs. *Radiance Cookbook*. Jaloxa. http://www.jaloxa.eu/resources/radiance/documentation/index.shtml. May, 2014

C. F. Reinhart. *Tutorial on the Use of Daysim Simulations for Sustainable Design*. Chapters 1 and 2. Harvard Desigh School. https://dl.dropboxusercontent.com/u/16228160/Daysim3.0.Tutorial.pdf. April, 2010.

C. F. Reinhart et al. *Dynamic Daylight Performance Metrics for Sustainable Building Design*. National Research Council Canada. http://www.arch.mcgill.ca/prof/sampson/arch447/fall2007/Readings/2-Dynamic%20Daylight%20Metrics.pdf. July, 2006.

Appendix G

Matlab-script

This appendix presents the general MATLAB-script written to plot and evaluate the results from the daylight simulations. The script reads an Excel-file containing numeric results from the simulation. The script is made in such a way that the user needs only redefine the name of the result-file and the plot-legend titles.

```
clear all; close all; clc
% -------------------------
% Written by Örn Erlendsson
% Date: 2014.04.28
% Distribution: Allowed
% -------------------------
% Note: Parameters that should be changed are filename, CF and legend!
%% Read result-file
filename = 'AtriumGlz60.xlsx'; resultSheet = 'CompareResults';
[data,text,raw] = xlsread(filename,resultSheet);
resDATAcell = {data}; % Store the results in cells
[A B] = size(data);
CF = 3; % Number of comparison floors
NP = A/CF; % Number of points per orientation per comparison floor
TP = B/4; % Number of test parameters
P = 1:NP:A; % Line in which the results start for each floor of interest
RES = cell(1,TP); % Size of result cells
% Store the results in cells
for i = 1:length(P)
    RES(:,i) = {data(P(i):P(i)+NP-1,1:B)};
end
% Get results from cells:
RESb = cell2mat(RES(1)); % Bottom floor results
RESm = cell2mat(RES(2)); % Middle floor results
RESt = cell2mat(RES(3)); % Top floor results
T = 1:4:4*TP; % Column number for first orientation
RESs = cell(CF,length(T)); % Size of result cells
% Store the results in cells for each floor:
for i = 1:length(T)
    RESs(1,i) = {RESb(:,T(i):T(i)+3)};
    RESs(2,i) = {RESm(:,T(i):T(i)+3)};
```

```
    RESSs(3,i) = {RESt(:,T(i):T(i)+3)};
end
%% Get results from each floor and orientation
% Bottom floor results per orientation:
b = cell2mat(RESSs(1,:)); n = 1;
for i = 1:4:B
    Sb(:,n) = b(:,i); Nb(:,n) = b(:,i+1); Eb(:,n) = b(:,i+2);
    n = n+1; end
% Middle floor results per orientation:
m = cell2mat(RESSs(2,:));
n = 1;
for i = 1:4:B
    Sm(:,n) = m(:,i); Nm(:,n) = m(:,i+1); Em(:,n) = m(:,i+2);
    n = n+1; end
% Top floor results per orientation:
t = cell2mat(RESSs(3,:));
n = 1;
for i = 1:4:B
    St(:,n) = t(:,i); Nt(:,n) = t(:,i+1); Et(:,n) = t(:,i+2);
    n = n+1; end
%% Plot results
cc=lines(TP); % Color matrix
lineST = cellstr(char('-','-.','--',':','-',...
    '-.','--',':','-','-.','--',':')); % Line-style
% Marker-style:
markerST = ['o','s','d','^','p','v','<','h','>','x','+','*'];
dd = 0.5:9.5; % Distance of simulation points
floor = {'Bottom' 'Middle' 'Top'}; % Floors of interest
O = {'South' 'North' 'East'}; % Orientations of interest
% Plot each orientation for each floor of interest
for f = 1:9
    figure(f)
    if f == 1
        for i = 1:TP
            o = 1;
            plot(dd,Sb(:,i),[lineST{i} markerST(i)],'color',cc(i,:),...
                'MarkerFaceColor',cc(i,:),'LineWidth',1.4)
            hold on
            title([char(floor(1)),' floor - ',char(O(o))]); end
    elseif f == 2
        for i = 1:TP
            o = 2;
            plot(dd,Nb(:,i),[lineST{i} markerST(i)],'color',cc(i,:),...
                'MarkerFaceColor',cc(i,:),'LineWidth',1.4)
            hold on
            title([char(floor(1)),' floor - ',char(O(o))]); end
    elseif f == 3
        o = 3;
        for i = 1:TP
            plot(dd,Eb(:,i),[lineST{i} markerST(i)],'color',cc(i,:),...
                'MarkerFaceColor',cc(i,:),'LineWidth',1.4)
            hold on
            title([char(floor(1)),' floor - ',char(O(o))]); end
    elseif f == 4
```

```
        for i = 1:TP
            o = 1;
            plot(dd,Sm(:,i),[lineST{i} markerST(i)],'color',cc(i,:),...
                'MarkerFaceColor',cc(i,:),'LineWidth',1.4)
            hold on
            title([char(floor(2)),' floor - ',char(O(o))]); end
    elseif f == 5
        for i = 1:TP
            o = 2;
            plot(dd,Nm(:,i),[lineST{i} markerST(i)],'color',cc(i,:),...
                'MarkerFaceColor',cc(i,:),'LineWidth',1.4)
            hold on
            title([char(floor(2)),' floor - ',char(O(o))]); end
    elseif f == 6
        for i = 1:TP
            o = 3;
            plot(dd,Em(:,i),[lineST{i} markerST(i)],'color',cc(i,:),...
                'MarkerFaceColor',cc(i,:),'LineWidth',1.4)
            hold on
            title([char(floor(2)),' floor - ',char(O(o))]); end
    elseif f == 7
        for i = 1:TP
            o = 1;
            plot(dd,St(:,i),[lineST{i} markerST(i)],'color',cc(i,:),...
                'MarkerFaceColor',cc(i,:),'LineWidth',1.4)
            hold on
            title([char(floor(3)),' floor - ',char(O(o))]); end
    elseif f == 8
        for i = 1:TP
            o = 2;
            plot(dd,Nt(:,i),[lineST{i} markerST(i)],'color',cc(i,:),...
                'MarkerFaceColor',cc(i,:),'LineWidth',1.4)
            hold on
            title([char(floor(3)),' floor - ',char(O(o))]); end
    elseif f == 9
        for i = 1:TP
            o = 3;
            plot(dd,Et(:,i),[lineST{i} markerST(i)],'color',cc(i,:),...
                'MarkerFaceColor',cc(i,:),'LineWidth',1.4)
            hold on
            title([char(floor(3)),' floor - ',char(O(o))]); end
    end
    grid off
    %% Change legend to fit the simulated data!!!!
    leg = legend('60%, 60%, 60%, 60%, 60%','20%, 40%, 60%, 80%, 95%',...
        '95%, 95%, 95%, 95%, 95%');
    xlabel('Distance from atrium wall [m]','FontSize',14)
    ylabel('Daylight autonomy [%]','FontSize',14)
    axis([min(dd) max(dd) 0 100])
    hold off
    saveas(gcf,['Figure',num2str(f)],'pdf')
end
```

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