Master's thesis

NTNU
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Window design optimization in terms of daylight and thermal comfort for a typical Norwegian residential building

Master's thesis in Civil and Environmental Engineering
Supervisor: Bozena Dorota Hrynyszyn
June 2021

NTNU
Kunnskap for en bedre verden

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Preface

This master thesis, within the specialization TBA4905 Building and Material Engineering, has been completed in the last semester of the study in Civil and Environmental Engineering at the Norwegian University of Science and Technology.
The human comfort in residential buildings has been a subject of interest and passion for several years of my study. Tracing back to my bachelor thesis, which is about residential design for a better health. I got a revelation about the importance of inclusive design where the human needs are in focus. In addition to my interest in building physics, it became most of the reasons why I chose to write this thesis. This thesis is also a product of my specialization project during the fall of 2020. This project examined the construction industry's experiences with building design to achieve requirements for thermal comfort and daylight.

I would like to send a special thank you to my supervisor Associate Professor Bozena Dorota Hrynyszyn, who has provided much help during the specialization project, this thesis as well as production of the scientific paper. She has been very committed to my work and with weekly digital meetings and she has been a great sparring partner. Her expertise within PHPP-Passive House Planning Package has been a great help when creating the different simulation cases.

Finally I would like to thank all my classmates for the amazing years at NTNU. Special thanks to friends and family which has contributed with proof-reading and support during this semester.

Trondheim, July 1, 2021

Tony Arntsen

Sammendrag

Vindusdesign påvirker dagslystilgjengeligheten, termisk komfort i tillegg til energibehovet til bygningen. Et uheldig vindusdesign kan medføre at et bygg går fra god til dårlig ytelse.

I denne masteroppgaven er norske og internasjonale standarder og reguleringer sammenliknet med tanke på kriteriene satt for termisk komfort og dagslys. For å undersøke hvordan disse reguleringene og standardene tilrettelegger for konsekvente ytelser, er det utført et simuleringsstudie av en case-bygning tegnet av Norgeshus. I den undersøkte bygningen, Dråpen, er det valgt ut syv kritiske rom basert på dems personopphold. Simuleringene er utført ved hjelp av IDA ICE, PHPP og TEK-Sjekk. I IDA ICE er hvert individuelle rom simulert, mens hele bygningnen bygningen er betraktet som en sone i PHPP og TEK-Sjekk. Det er totalt konstruert 11 ulike case. Disse består av stedsavhengige scenarioer, endring i vindusegenskaper, design og bygningskropp, i tillegg til solskjermingsstrategi. Resultatene fra simuleringene munner ut i et optimalisert design av bygningen.

Resultatene avdekket at overoppheting og dagslys ofte gir motsigende resultater. Hvor god dagslystilgjengelighet kan resultere i dårlig termisk innemiljø, og omvendt. En bedre isolert byning gir et lavere årlig oppvarmingsbehov med kun marginale tap i dagslystilgjengelighet. En tettere konstruksjon medfører likevel til en risiko for overoppheting. Ved å installere utvendig solskjerming i stedet for innvendig som er i referansebygget, ble risikoen for overoppheting eliminert. En revisjon av vindusdesignet ved å øke andelen glass mot sør og fjerning av arealene mot nord, økte ytelsen for hele bygget. Dette understreker viktigheten med et godt vindusdesign. Den optimaliserte utgaven av bygningen besto av forbedring av bygnignskroppen, revidert vindusdesign, og bruk av utvendig solskjerming. Denne kombinasjonen resulterte i at alle kriterier ble oppfylt, hvorav oppvarmingsbehoved ble redusert med 26-40% i forhold til referensebygget. Ved å analysere resultatene i oppgaven, kommer det frem at kravene for dagslys ikke er forenelige, slik at reviderte krav for å sikre tilstrekkelig dagslys er å anbefale.

Summary

Window design affects the performance of daylight, thermal comfort as well as energy demand of the building. A unfortunate window design can overturn a high performance building to a building with poor performance.

In this thesis the Norwegian building code and international regulations and standards are compared regarding the criteria set for thermal comfort and daylight. To investigate how these regulations and standards facilitates consistent performance levels, a simulation study of a case building provided by Norgeshus has been examined. For the studied building, *Dråpen*, seven rooms are investigated as critical rooms based on their occupancy. The simulation process is done by IDA ICE, PHPP and TEK-Sjekk. Each room are simulated in IDA ICE, while the simulation is limited to the whole building zone in PHPP and TEK-Sjekk. In total, 11 case designs are made. The cases consist of site dependent scenarios, changes in window properties, design, and building body, as well as solar shading control. The results in the studied cases culminates into a optimized design for the studied building.

The results revealed that overheating and daylight often gives opposite results, where a good daylight performance can result in a poor thermal indoor environment and vice versa. A more insulated building has lower annual heating demand, with only marginal losses in daylight, but the tighter construction does increase the risk of overheating. By applying external blinds instead of the default internal blinds did eliminate the overheating. A revision of window design with more glazing area towards south and removing those to the north, increases the overall performance of the building, which highlights the importance of good window design. The optimized version of the building consists of improving the building envelope, a revised window design and external blinds. This combination fullfils every criteria evaluated, and lowers the annual heating demand by 26-40% compared to the reference case. When evaluating the results, this thesis show that the requirements for daylight are not consistent, and should be revised to secure adequate daylight performance.

Contents

Nomenclature

Symbol	Description	Unit
A_g	Glazing area	m^2
A_{BRA}	Usable floor space	m^2
CAV	Constant Air Volume	
DF	Daylight factor	%
LT	Light transmittance of the glass	%
MET	Metabolic activity	MET
$^{\circ}C$	Temperature Celsius	$^{\circ}C$
$\overline{DF}$	Average Daylight factor	%
d	Longer dimension of the calculation area	m
h^{-1}	Air change rate per hour	
p	Maximum grid size	m

Chapter 1

Introduction

1.1 Background

In a Norwegian residential building there are several parameters that influence the annual heating and cooling demand. The trend for sustainable building design is to make the buildings technical standard and heating systems as energy efficient as possible. Despite this trend it is important to understand how window design influence the building performance. A unfortunate window design can overturn a high performance building to a building with poor performance. Daylight provision reduces the energy demand for artificial lighting, and the window design affects the energy efficiency in terms of both annual heating demand and cooling demand. However, larger glazing area also increases the risk of overheating due to solar heat gain. Studies has identified that well insulated dwellings in present climate are at risk of overheating even for colder climates (Tian & Hrynyszyn 2020). There is a risk that the pursuit of very low annual heating demands are at expense of the indoor thermal comfort.

Daylight design has traditionally been treated separately. Good designs demands a more integrated approach, where daylight should be considered holistic and included in early-stage planning. Unless the daylight is integrated during the initial stages of building design there is a risk of buildings in future climate are more dependent on active cooling systems or buildings having poor daylight provision at expanse of other factors.

Global warming is a common concern, and the negative impact from the building industry has gathered more attention the last years. By 2015 the building industry constituted 40 % of the total energy consumption in Norway. Therefore it is important to plan sustainable and energy efficient solutions for the buildings. The future residential houses needs to be more dynamic and robust for the expected climate changes in the future. The European Commission stated that new and existing building stock needs to be smarter and more energy energy efficient. One of the key targets is to reduce the green-house gas emissions by 40 % (European Commission 2021).

1.2 Purpose

The purpose of this master thesis is to investigate how various design options for a typical Norwegian residential house influence the daylight provision, thermal comfort and annual heating demand. As a part of the analysis it is desired to expose potential incompatible requirements in the Norwegian Regulations on Technical Requirements for construction works.

The following research questions are formed with the desire to answer the purpose of this thesis:

- RQ1: How well does the criteria in TEK17 and NS-EN17037 facilitate good daylight performance for a typical Norwegian residential building?
- RQ2: What are the consequences of applying different design changes to a typical Norwegian residential building in terms of annual heating demand, thermal comfort and daylight provision?
- RQ3: What is the optimal design for the studied building when it comes to annual heating demand, thermal comfort and daylight provision?

1.3 Limitations

There are many measures that could have been included and studied in this thesis. This thesis does however focus on aspects which are relevant both in a design phase for residential buildings, but most important the conditions which are described in the regulations and is desired to be investigated. Case variants which only influences mostly one of the subjects is therefore not included. Since the daylight is calculated by the daylight factor, there is also limitations regarding the possible outputs because of the properties of the overcast sky model. Since availible IDA ICE version is 4.8 in this thesis, the functionality of IDA ICE 5 with dynamic climate simulation is not possible.

1.4 Structure

This master thesis is divided into 6 chapters, including the introduction. The chapter after the introduction reviews the Norwegian and international regulations and standards in therms of thermal comfort and daylight. This chapter also presents theory for the used simulation software in this thesis. Before the chapter ends with relevant literature.

The next chapter presents the methodology, and is divided into four sections. Firstly the studied building body is described. Thereafter the simulation cases for the case study is defined. The following section describes input parameters for the reference building, before each case are described in the next section. The method chapter ends with a description of the working methodology for adapting the building model for each software.

Chapter 4 contains the results of the simulation as well as discussion. The results are sorted based on the case number, in addition to the subjects of energy, thermal comfort and daylight. Based on the results in the case study, an optimized model of the building is created and simulated, where the results are presented in the end of the chapter.

Chapter 5 and 6 is the final part, where this thesis gives a conclusion and suggestion for future work.

Chapter 2

Review

2.1 Nordic climate

The solar radiation that hits the earth is equivalent to 15.000 times the total annual energy consumption for the entire earth. This solar energy can be utilized either in passive form or active. Using the solar heat gains through windows for space heating, and the solar radiation as substitute for artificial lighting is examples of passive utilization (SINTEF & KanEnergi 2014). Principles for active utilization could be solar thermal collectors that directly uses the solar energy to heat water that circuits the building for space heating and domestic hot water. Conversion of the solar energy to electricity in form of solar panels is also an example of active utilization (Lavenergiprogrammet 2020). Since Norway is a elongated country with various topography, the solar radiation is very dependent on localization and season. A large part of Norway is located north of the Arctic circle, where the sun does not set mid-summer, and does not rise mid-winter. This leads to big seasonal variations, and the possibility of solar exposure on the northern facade. Figure 1 illustrates the variation of solar irradiation in Norway for winter and summer conditions. The seasonal variations is an important aspect when considering the glazing area of a building. Windows can have a huge impact on the heating and cooling loads of a building, and influences the indoor thermal environment as well as the greenhouse gas emissions due to energy demand. Almost 40% of a buildings heating energy can be lost and up to 87% can be gained through windows (Lyons et al. 2013).

Figure 1: Daily solar irradiation on horizontal surface - January (left), July (right) (Rindal & Salvesen 2008)

2.2 Norwegian regulations

The Norwegian Building Regulations, TEK17, consists of a set of minimum properties and technical requirements that must be met in order to build legally. This building code defines functional regulations and performance criteria with attached pre-accepted performances which fulfills these requirements.

2.2.1 Thermal comfort

For thermal comfort there are two functional requirements which are relevant for design of residential dwellings. The following paragraphs are cited from TEK17:
§13-4 (1):

> *The thermal indoor climate in rooms intended for continuous occupancy shall be regulated in a manner that promotes health and satisfactory comfort when the rooms are used as intended*

§13-4 (2):

> *In rooms for continuous occupancy it must be possible to open at least one external window or door*

2.2.2 Daylight

TEK17 indicates two functional requirements that is considered to be relevant for building design. The following paragraphs are cited from TEK17.
§13-7 (1):

Construction works shall have adequate access to light

§13-7 (2):

Rooms for continuous occupancy shall have adequate access to daylight

The pre-accepted performances for §13-7 (2) gives two methods for achieving required performance. The first method is based on the average daylight factor DF which has to be minimum 2.0% for the most critical rooms. Calculations through simulations software has to validated according to CIE 171:2006 and the premises defined in NS-EN 12464-1:2011 chapter 4.4. The following equation needs to be fulfilled for selected rooms (Direktoratet for byggkvalitet 2021):

$$\overline{DF} = 2.0\% \tag{1}$$

The premises from the European light standard NS-EN 12464-1:2011 describe how the grid systems shall be created. The maximum grid size is defined by the following equation (Standard Norge 2011):

$$p = 0.2 \times 5^{log_{10}(d)} \tag{2}$$

Where:
p = Maximum grid size [m]
d = Longer dimension of the calculation area

Alternatively the daylight requirement can be achieved with a simplified simplified method (Direktoratet for byggkvalitet 2021):

$$A_g \geq 0.07 \cdot A_{BRA} \cdot LT \tag{3}$$

Where:
A_g = Glazing area [m^2]

A_{BRA} = Usable floor space, including area of protruding building parts [m^2]
LT= $Lighttransmittanceoftheglass[\%]$

2.3 International regulations

2.3.1 Thermal comfort

NS-EN 16798-1:2019 states that for defining the thermal environment, the criteria shall be based on the indices PMV-PPD from EN ISO 7730. For buildings without mechanical cooling the criteria could either be specified by the default method from EN ISO 7730, or by using the adaptive method. The adaptive method also considers the adaptation effects for occupant behavior when experiencing thermal discomfort. This method applies to buildings with sedentary activities where the occupant can adapt to the thermal conditions by either ventilating through windows or change of clothing. The collected data material is based on studies conducted in office buildings, but the standard ensures that the method also is applicable for similar spaces, such as residential buildings.

$$\Theta_{rm} = (\Theta_{ed-1}+0,8\Theta_{ed-2}+0,6\Theta_{ed-3}+0,5\Theta_{ed-4}+0,4\Theta_{ed-5}+0,3\Theta_{ed-6}+0,2\Theta_{ed-7})/3,8 \quad (4)$$

Category I	upper limit	$\Theta_o = 0,33\Theta_{rm} + 18,8 + 2$
	lower limit	$\Theta_o = 0,33\Theta_{rm} + 18,8 - 3$
Category II	upper limit	$\Theta_o = 0,33\Theta_{rm} + 18,8 + 3$
	lower limit	$\Theta_o = 0,33\Theta_{rm} + 18,8 - 4$
Category III	upper limit	$\Theta_o = 0,33\Theta_{rm} + 18,8 + 4$
	lower limit	$\Theta_o = 0,33\Theta_{rm} + 18,8 - 5$

Table 2: Adaptive comfort temperatures categories for free running buildings (Standard Norge 2019)

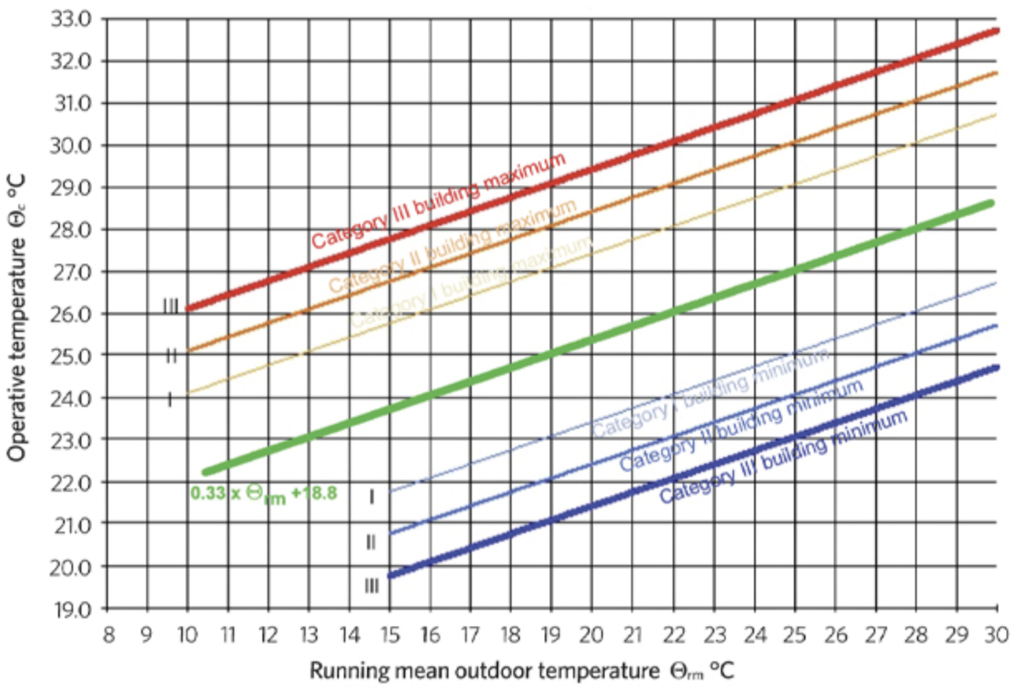


Figure 2: Acceptable operative temperature ranges based on temperatures from table 2 (CIBSE 2017)

2.3.2 Daylight

The European standard for daylight in Buildings EN 17037:2018 is researched and prepared by Technical Committee CEN/TC 169 "Light and Lighting". The purpose of this paper is to facilitate a platform to secure adequate daylight provision in building design. The recommendations are categorized i different ambition levels as well as addressing challenging interfaces against view out, glare and exposure to sunlight. The standard was verified as a Norwegian Standard in February 2019. Since it has authority as a Norwegian Standard it will be referred to as NS-EN 17037:2018 further in this thesis.

Table A.1 — Recommendations of daylight provision by daylight openings in vertical and inclined surface

Level of recommendation for vertical and inclined daylight opening	Target illuminance E_T lx	Fraction of space for target level $F_{plane,\%}$	Minimum target illuminance E_{TM} lx	Fraction of space for minimum target level $F_{plane,\%}$	Fraction of daylight hours $F_{time,\%}$
Minimum	300	50 %	100	95 %	50 %
Medium	500	50 %	300	95 %	50 %
High	750	50 %	500	95 %	50 %

NOTE Table A.3 gives target daylight factor (D_T) and minimum target daylight factor (D_{TM}) corresponding to target illuminance level and minimum target illuminance, respectively, for the CEN capital cities.

Figure 3: Recommended values for daylight provision

The table shown in figure 3 from the standard gives recommended values based on desired level of ambition. The values for measurement is expressed in terms of illuminance measured in lux. Table A.3 in figure 4 gives corresponding daylight factor values for respective CEN capital cities.

Nation	**Capital** [a]	**Geographical latitude** φ [°]	**Median External Diffuse Illuminance** $E_{v,d,med}$	***D* to exceed 100 lx**	***D* to exceed 300 lx**	***D* to exceed 500 lx**	***D* to exceed 750 lx**
Norway	Oslo	59,90	12 400	0,8 %	2,4 %	4,0 %	6,0 %

Figure 4: Recommended values for daylight provision

2.4 BPS software

2.4.1 IDA ICE

IDA ICE (IDA Indoor Climate and Energy) is a building energy modeling software for energy and indoor climate developed by EQUA Simulation AB (EQUA 2021*b*). It can perform detailed calculation for energy use and indoor thermal climate by using a whole-year dynamic multi-zone simulation.

There are several formats for importing data into the simulation platform. It is possible to directly import (*.dwg, *.dxf, *.dwf, *.skp, *.3ds, *.jpeg/.jpg, *.png, *.psd) files. IDA ICE has compatibility for import of Industry Foundation Classes (IFC) files as well. By the current version used in this thesis, version 4.8, IDA ICE supports IFC-formats IFC2x, IFC2x2 and IFC2x3. IDA ICE imports the geometry of the defined solid object from the CAD-application. The most important geometries for simulation are walls, windows, doors and roofs. To achieve a fluent import, IDA ICE requires that IFC-spaces are pre-defined in BIM in order to create simulation zones.

2.4.2 PHPP

The Passive House Planning Package is developed by the Passive House Institute. It is a design tool with collection of many defined building physics algorihms. The tool consists of interlinked worksheets, with format familiar to Microsoft Excel. The calculations are instantaneous, so the effect of implementing a parameter change can immediately bee seen by the user. Mainly it provides results regarding energy demand and thermal comfort, but has many outputs within the different worksheets (Passipedia 2020).

The Passive House Institute has developed the plugin designPH to provide a 3D interface and import compatibility from Sketchup (Passipedia 2019). There is also created a BIM tool (bim2PH) to connect BIM through IFC import to PHPP. Relevant information can then be transferred from 3d models in bim2PH to the worksheets in PHPP. Bim2PH has project templates availible for Revit, ArchiCad, Vectorworks and Rhinoceros in order to include missing energy efficiency properties to building models (Passivhaus institut 2021).

2.4.3 TEK-SJEKK

TEK-Sjekk is a tool for validating buildings up against criteria in TEK17 and NS 3700. The tool can also calculate and verify if criteria for energy supply and thermal comfort are met. Just as PHPP it has workspace in a Microsoft Excel spreadsheet, with built in macros. The energy calculations are perform in accordance to NS 3031, and the algorithm is a dynamic hour calculation as defined in NS-EN ISO 13790 (Byggforskserien 2016). The program can import building geometry from BIM in formats: SketchUp Collada (.DAE), Green Building gbXML (.XML) and IFC-files (.IFC). DDS-CAD, Autodesk Revit and ArchiCad offers export options which can be used in TEK-Sjekk (Byggforskserien 2016).

2.5 Relevant litterature

The single-family houses either as detached houses, semi-detached houses or terraced houses represent 69.7% of the total residential buildings in Norway 2021 (Statistisk Sentralbyrå 2021). These groups are also most demanding in terms of energy consumption. In 2014, a detached house used 236% more in total energy use compared to an apartment block (Statistisk Sentralbyrå 2014).

Daylight have been found to have positive influence on the human health. There are at least two biological parameters that are influenced by the exposure of sunlight. When the sunlight touches the human skin, vitamin D is produced and is linked to many health benefits (Kauffman 2009). Lansdowne & Provost (1998) claims that it also improves mood through production of serotonin. The second parameter is how the daylight affects the circadian system. The biological clock are sensitive to wavelengths in the blue spectrum, which the daylight naturally covers. In addition to the biological effect, there is also studies that covers the salutogenic effect of daylight. (Vandewalle et al. 2009). Overall this implies that the daylight availability in houses influences the well-being of the occupant. RIF et al. RIF (2020) recommends based on their daylight study, that the Vertical Sky Component (VSC) should be used to assess the influence of neighbourign buildings in early stage planning. There is many factors that influence the daylight environment in the building, such as:

- Geographic location
- Orientation
- Wall thickness
- Obstructing surroundings
- Amount of windows
- Glazing properties

- Shading devices
- Facade cantilever

When calculating the daylight factor, it is evaluated for a CIE overcast sky. In other words, the daylight factor is a quantification measure of diffuse daylight. For this sky model, the daylight is independent of window orientation and climate. Direct sunlight and need for dynamic solar shading is therefore ignored. The luminance changes with altitude and is three times as bright at zenith than near the horizon (CLEAR 2021).

Chapter 3

Method

Norwegian residential housing is regulated by TEK17 and for this thesis it is most relevant to look into the given performance performance criteria for daylight and thermal comfort, and how this affect the heating demand. In order to investigate how well TEK17 facilitates consistent good performance in terms of daylight and thermal comfort, the methodology in this thesis is split up in different parts. The aim is to first understand the impact of each parameter before creating a optimized version of the building.

The first step is to model a case reference building based on a real house model delivered by Norgeshus. The same building body will then be applied with a set of predefined measures.

The steps in the case study will then culminate in an optimized version of the studied building, based on daylight provision, thermal comfort and heating demand.

3.1 Defining building bodies

As mentioned before, the case study will be based on an existing detached house concept designed by Norgeshus. The house model used in this thesis is Dråpen.

3.1.1 Dråpen

Dråpen is a typical Norwegian residential building. The total floor area is 140 m^2 over two floors. Common areas such as kitchen, dining area and living room is located on the ground floor, while bedrooms are situated on the first floor. Figure 5 displays a rendered view of the house model. See figure 6 for layout of the ground floor and 7 for the first floor.

Figure 5: Case building representing a typical residential building in Norway (Source: Norgeshus)

Figure 6: Ground floor layout (Source: Norgeshus)

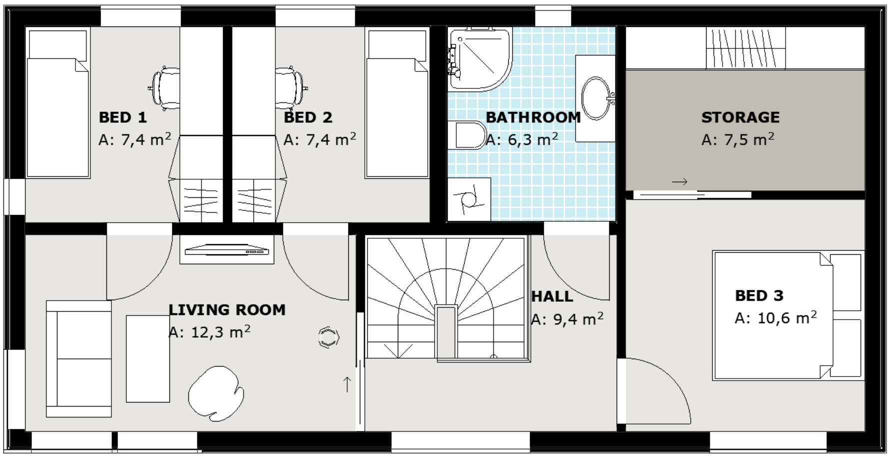


Figure 7: First floor layout (Source: Norgeshus)

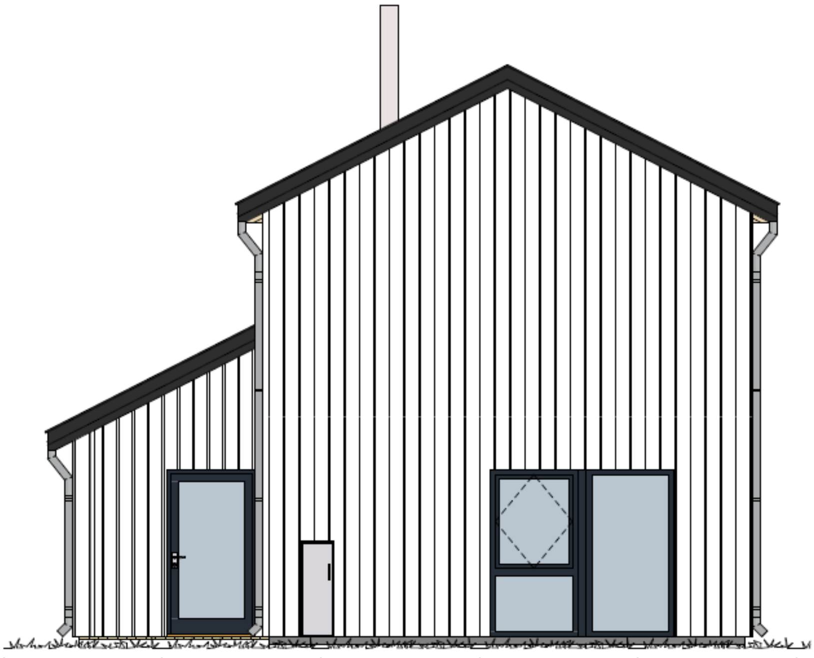


Figure 8: Northern facade (Source: Norgeshus)

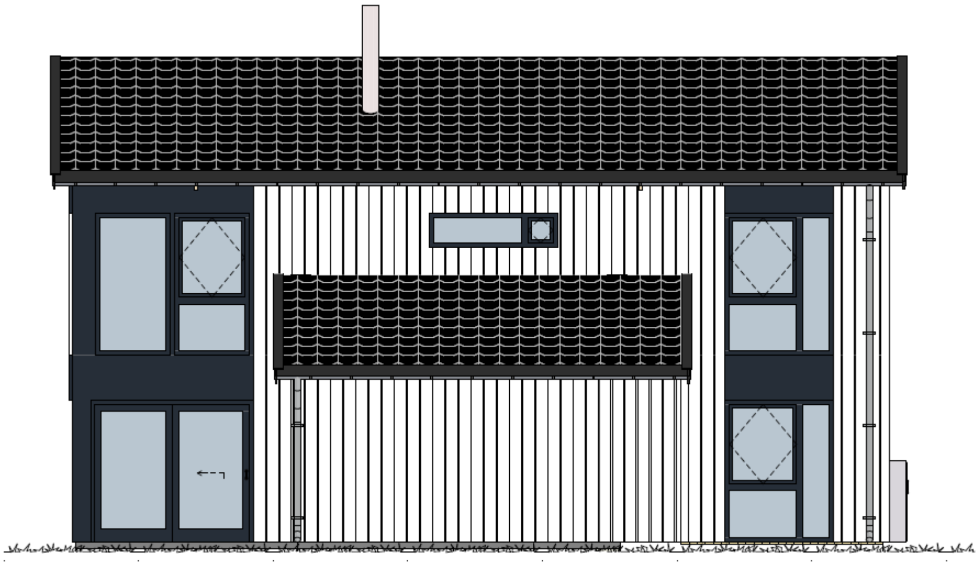


Figure 9: Eastern facade (Source: Norgeshus)

Figure 10: Southern facade (Source: Norgeshus)

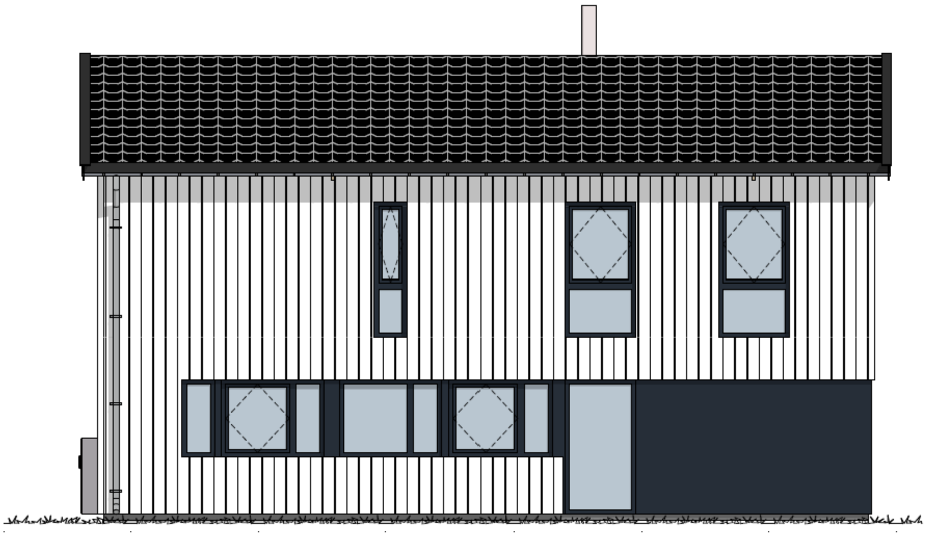


Figure 11: Western facade (Source: Norgeshus)

The window area for each facade is as follows:

- North: 6.8 [m^2]
- East: 17.1 [m^2]
- South 12.0 [m^2]
- West 11.8 [m^2]

In order to facilitate results which are easily comparable to both Norwegian regulations and European standards, only the Daylight Factor (DF) has been examined. The daylight factor presumes the illumination on a horizontal reference plane i the room expressed in percentage of the simultanous illumination on an outdoor horizontal plane with no casting shadows (Thue 2016). This is a simpler approach than a dynamic climate derived illuminance calculation. The DF method is calculated for a CIE overcast sky, and is therefore independent on window orientation. For this sky model the luminance changes with altitude and is three times as bright at zenith than near the horizon (CLEAR 2021). Even though this method does not comply with the actual daylight environment, it still represents the unfavourable case and will unlikely give results better than actual daylight performance (Lee et al. 2019).

As previously mentioned, TEK17 gives two functional requirements for thermal comfort. The guidance for fulfilment of the functional requirement states that the performance is adequate if the exceedance of highest temperature does not surpass 50 hours in a normal year. The acceptance criterion for NS 16798 is based on CIBSE TM52, where the limit of unacceptable hours is set to be 3% of occupancy hours (CIBSE 2013). In other words, based on used occupancy schedule this corresponds to a maximum of 86 hours for dayrooms and 125 hours for bedrooms.

3.2 Defining cases

The following section describes the selected cases. The reference model is named case 0 and is equal to the distributed model from Norgeshus. Case 1 aims to investigate the the effect of only changing the orientation of the building, which is relevant for a lot of building scenarios. This is done by rotating the building 90° counter-clockwise, so that the longer facade is oriented to the south. A typical measure for pursuing better energy efficiency is by improving the building envelope with more insulation. Thus, Case 2 investigates this scenario by changing original insulation thickness (200mm) to 350mm. Case 3 and 4 represents cases for the boundary criteria that are allowed for the simplified method in §13-7(2) TEK17. Case 5, 6 and 8 investigates measures for solar control. Since the daylight factor is calculated for an overcast sky, the affect of having different shading strategies are neglected, since they don't influence the daylight calculation. A revised window design, case 7, aims to discover how strategically changing the window design affects the performance of the same building body. Case 9 and 10 investigate the effect of new technology based on discoveries from Lee et al. (2021). One of the findings was that an inclination of -10° have the most PV-production. Hence, the choice of two alternative cases for comparison. Case 11 examines how changing from internal shading to external affects the solar control. Every case are presented in table 3. For each case of Dråpen only mentioned parameter changes has been applied. The remaining model is equivalent to the reference model. The models is edited manually in IDA ICE.

Case nr	Case name	Case description
Case 0	Reference model	Original model with default values
Case 1	Oriented	Building model is oriented 90 degrees counter-clockwise
Case 2	Thicker walls	Improving the building envelope. 350mm insulation in walls
Case 3	Shading object	Maximum accepted obstruction angle in the horizon for the simplified method in TEK17
Case 4	Minimum glazing area	Minimum glazing criterion for the simplified method for each room
Case 5	Low light transmittance	New glazing properties: LT = 61 and g-factor: 33
Case 6	Medium light transmittance	New glazing properties: LT = 27 and g-factor: 16
Case 7	Revised window design	Removal of windows facing north, and more windows facing south
Case 8	Static external overhang	External overhang with depth of 1m
Case 9	Light shelf (horizontal)	Mounted on windows >1m wide
Case 10	Light shelf (-10 degree inclination)	Mounted on windows >1m wide. Rotated 10 degree towards the sun.
Case 11	External shading	External blinds with solar gain factor 0.14 (0.65 in case 0)

Table 3: Overview of simulated cases

3.3 Description of case 0

The reference model is created with energy measures listed in table 5

Input parameter	**Values for reference case**
U-value exterior walls (200mm)	0.198 W/m^2K
U-value roof	0.127 W/m^2K
U-value floor	0.094 W/m^2K
U-value windows and doors	0.900 W/m^2K
Window and door ratio of usable space	36.2 %
Temperature efficiency of heat recovery	80 %
Air leakage rate per hour at 50 Pa pressure difference	1.0 h^{-1}
Normalized thermal bridge	0.05 W/m^2K

Table 4: Input values regarding the building body for reference model

Input parameter	Condition
Reflection factor floor	0.2
Reflection factor wall	0.5
Reflection factor ceiling	0.7
Reflection factor outside ground	0.2
Room height	2.5m
Measuring plane	0.8m
Excluded perimeter	0.5m
Precision of daylight simulation	High
Location	Oslo
Default glazing	LT = 73 and g-factor = 57
Shading device (default)	Internal blinds
Occupant activity	1.0 MET
Occupant clothing	0.85 $\pm$0.25
Ventilation rate (CAV)	$1.2m^3/h \cdot m^2$
Heating set point, living spaces	20 °C
Heating set point, other spaces	16 °C

Table 5: System parameters for reference model

Internal heat gains from occupants, equipments and lighting are defined according to values set in the Norwegian technical standard, SN-NSPEK 3031:2020 (Standard Norge 2020). The deterministic occupancy schedule is based on schedules from Nord et al. (2017) and adapted to fit the annual normalized values in the standard.

Since energy is not the main focus of this thesis, the inputs for energy calculation is either simplified or set by default. For the model in IDA ICE, each zone is heated by electric radiators. The setpoints are based on recommended values in annex B in NS-EN 16798-1:2019 (Standard Norge 2019). The set point temperature is therefore different between living spaces and other spaces. By deafult the reference model is applied with internal blinds that are PI-controlled with activation when operative temperatures reaches 23°C. Window open when operative temperature exceeds 25°C. Windows that are openable are displayed in figure 8, 9, 10 and 11. Figure 12 and 13 illustrates the imported floor plan of Dråpen in IDA ICE.

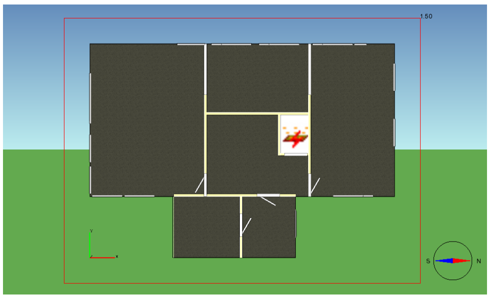


Figure 12: Ground floor in IDA ICE

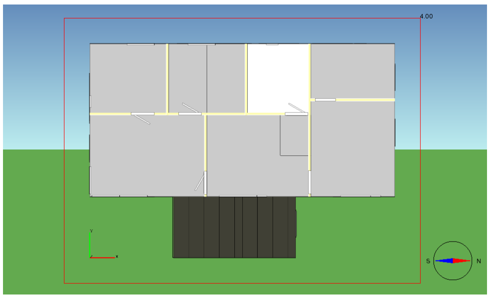


Figure 13: First floor in IDA ICE

3.3.1 Case 1

For case 1 the model investigates how only changing the orientation influence the daylight provision, thermal comfort and annual heating demand. The model is oriented 90° counter-clockwise so that the longest facade is oriented south. Most of the occupied zones has a wall facing this south orientation, so it is to expect that solar heat gain will contribute through the glazing areas.

3.3.2 Case 2

The second case is based on improving the building envelope. In other words, thicker walls, less thermal bridges and tighter construction. By applying these changes the model becomes for air tight and will become more sensitive in terms of the indoor thermal environment. How much the thicker walls influence the daylight provision in critical rooms is also of interest. The walls in this case has a thickness of 350mm and the normalized thermal bridge is set to 0.03 $\frac{W}{mK}$. Infiltration has a value of 0.6 h^{-1}.

3.3.3 Case 3

Based on the formulation in TEK17, the simplified method for daylight accepts obstructions up to 45 degrees measured from horizontal plane. Case 3 therefore investigates how much such obstacles influence the building performance. In IDA-ICE it has been modelled 3 walls that are 9.2m tall, and placed 8m from the building model. The obstacles are not continous in the corners to represent a more realistic scenario of a neighbourhood. See figure 14 for illustration in IDA ICE. The walls have zero transparency and reflection to imitate worst case scenario as well as harmonize with input possibilities in PHPP and TEK-Sjekk. Since the obstruction height is regulated by the windows on the ground floor, the windows on the first floor will experience less shading.

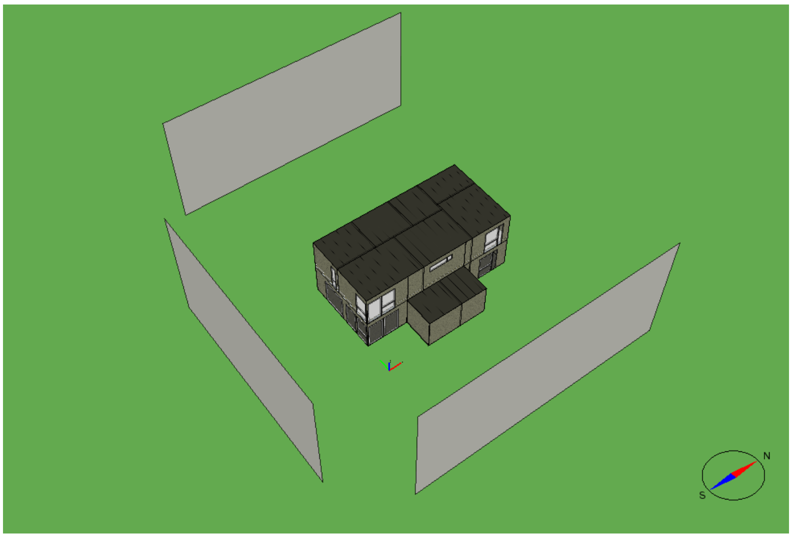


Figure 14: Illustration of obstacles in IDA ICE

3.3.4 Case 4

In relation to the previous case, this case investigates a boundary condition in TEK17. Case 4 applies the minimum criterion that is accepted through the simplified method for each room. Glazing area for each room is therefore equal to the formula:

$$A_g = 0.07 \cdot A_{BRA} \cdot LT \tag{5}$$

The new distribution of windows does not take into account the placement of windows in reference case. Every window has a fixed width of 1m, and placed on the midpoint between internal walls in the room.

3.3.5 Case 5

Since light transmission through glazing area is a parameter in the simplified method, it has been constructed two separate cases with different glazing properties. Appropriate values from window manufacturers is used in the simulation integrated in PHPP.
For case 5 the g-factor is set to 16 and light transmittance is set to 27. This values has been applied to every window.

3.3.6 Case 6

Case 6 is very similar to the previous case, but the g-factor is 32, and light transmittance is 59.

3.3.7 Case 7

In case 7, the window design has been revised. All the windows facing north has been removed, and some are removed on the western and eastern facade. More windows are placed on the southern facade. The reason for this is to try to minimize the heat losses through the windows, and exploiting as much of the passive solar heat as possible. Following changes is implemented for each facade:

North: $6.8 \rightarrow 0$ $[m^2]$
East: $17.1 \rightarrow 10.8$ $[m^2]$
South: $12.0 \rightarrow 26.5$ $[m^2]$
West: $11.8 \rightarrow 5.6$ $[m^2]$

3.3.8 Case 8

A measure to reduce the risk of overheating is to apply shading devices. In case 8 there is modelled a static external shading overhang over the windows. The overhang has a depth of 1m and is distributed along the entire building perimeter over the windows. The reason for covering the entire perimeter is to assure that every window gets the same shadowing effect independent of neighbouring windows. This case could also represent a scenario similar to where the balcony is located over the window.

3.3.9 Case 9

A method to further reduce the need for artificial lighting is to use light shelves to distribute daylight further in the room. This case simulates a model where windows have a light shelf mounted 1,8m over floor plan. The shelves are angled horizontally with a specular reflectance of 0.85. Depth of the light shelves are 0,52m. Based on a study by Lee et al. (2021), the light shelves have attached PV-modules in order to exploit the solar energy. The attached PV-module ratio is 100%.
In case 9 and 10 there is modeled light shelves that are mounted on the windows wider than 1m. PHPP and TEK-sjekk are not compatible to model such an scenario because of the advanced variables. IDA ICE does neither primarily support implementation of light shelves with attached PV-modules. IDA ICE can only model one singular PV-module for every simulation. In order to make it work and as accurate as possible, the energy simulation has been done in several steps, with a individual simulation for every light shelf. The PV-production was then summarized for every individual step, and represented as a total production for Case 9.

3.3.10 Case 10

The PV-module power generation had the best results when inclined -10° during summer (Lee et al. 2021). It also prevents the risk of potential glare issues. Same methodology as in case 9.

3.3.11 Case 11 - External shading

Daylight factor is not influenced by the shading devices since the daylight simulation for overcast skies calculates with deactivated shading. They do however affect the transmittance of solar radiation. Thus, a case for external shading will only consider energy and thermal comfort perspective.

3.4 Software

In order to perform simulations it was necessary to compare the compatibility of different softwares.

For verification a third-party software called SimpleBIM has been used. The building performance simulations were conducted by using the software IDA-ICE (EQUA 2021*b*). For the case study, IFC-models from ArchiCAD were imported to IDA-ICE with slight modifications through SimpleBIM. SimpleBIM has a add-on which addresses compatibility issues with IDA-ICE and enables the possibility of modifying the model to be validated for usage in IDA-ICE.

The daylight calculations were executed with the integrated Radiance simulation tool (EQUA 2021*a*). In order to facilitate results which are easily comparable to both Norwegian regulations and European standards, only the Daylight Factor (DF) has been examined. The daylight factor presumes the illumination on a horizontal reference plane in the room expressed in percentage of the simultaneous illumination on an outdoor horizontal plane with no casting shadows (Thue 2016). This is a simpler approach than a dynamic, climate derived illuminance calculation. The DF method is calculated for a CIE overcast sky, and is therefore independent on window orientation. For this sky model the luminance changes with altitude and is three times as bright at zenith than near the horizon (CLEAR 2021). Even though this method does not comply with the actual daylight environment, it still represents the unfavourable case and will unlikely give results better than actual daylight performance (Lee et al. 2019).

3.4.1 Adaptation to building model

In figure 15 it is illustrated the work methodology for creating the different models. Data material for the studied building were distributed by Norgeshus. IDA-ICE has the possibility of importing the geometric model from ArchiCad, so the work flow was based upon validating the exported geometry from ArchiCad through SimpleBIM. However, the import did only transfer the building geometry, so technical data and properties of the building envelope had to be edited manually. With an additional plug-in, PHPP has also the possibility of importing the geometric model, but since this plug-in was not provided for this thesis, the model was created manually, based on data material from Norgeshus. Norgeshus delivered their calculation file in TEK-Sjekk for the reference building. This was used as the reference, and adapted for each case.

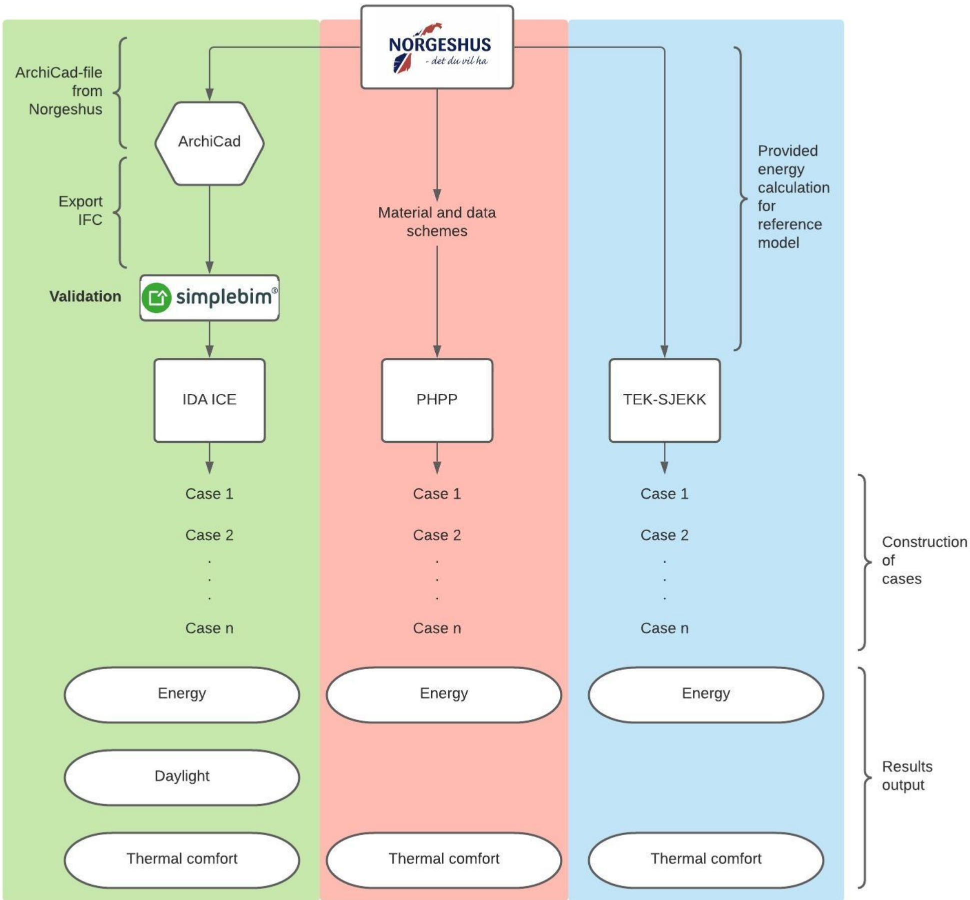


Figure 15: Flow chart of simulation methodology for each software

Chapter 4

Results and discussion

In this chapter the simulation results will be presented. Each case are divided into sections for Energy, Thermal comfort and Daylight. In the Energy section the heating demand is collected from IDA ICE, PHPP and TEK-sjekk. The presented Heating demand is total of energy for space heating and ventilation. Based on regulations and criteria in sections 2.2.1 and 2.3.1 the thermal comfort results are displayed with hours exceeding 26 degrees (IDA ICE), unacceptable hours according to category IV in NS-EN 16798-1:2019 (IDA ICE), Frequency of overheating (PHPP) and hours exceeding 26 degrees (TEK-sjekk). The results from daylight simulation are calculated for each individual room considered in Dråpen. The results are evaluated up against the criteria in TEK17 and NS-EN 17037. Since the softwares does not share the same functionalities they deviate in how they divide the calculated zones. While IDA-ICE calculates for each room, PHPP and TEK-sjekk only provide results for the building as a whole. Thus, not every case are compatible for every software.

4.1 Case 0 - Reference model

4.1.1 Energy

Table 6 shows the annual heating demand for the reference case. IDA ICE deviates somewhat to the results from PHPP and TEK-sjekk. A possible reason for this could be the set up for the building model in each software. IDA ICE is the only software of the three that has imported exact building geometry from IFC. It is also the only software that calculates with multiple zoning.

Software	Annual heating demand $[kWh/m^2]$
IDA-ICE	43.9
PHPP	46.5
TEK-sjekk	47.6

Table 6: Heating demand for case 0

4.1.2 Thermal comfort

Based on the results in table 7 there is only one room that fulfills the requirements of maximum 50 hours of hours exceeding 26 degrees. It is not surprising that it is Bed 3 which is located on the northeastern corner of the building and only has windows facing east. It has theoretically the lowest amount of solar heat gain through the windows. Unacceptable hours agrees with the output of Bed 3 beeing the best performing room with only 13 hours. Even though only one room is approved by IDA ICE, PHPP calculates the overheating hours to be 44 hours. TEK-sjekk may have a closer assumption like IDA ICE, that the total of the building does not meet the requirement.

	IDA-ICE		PHPP	TEK-Sjekk
	Hours exceeding 26 degrees [h]	Unacceptable hours (IV)[h]	Frequency of overheating [%]	Hours exceeding 26 degrees [h]
Kitchen	67	53	0,5 % $\approx 44h$	92
Dining room	69	38		
Living room g.fl	54	67		
Bed 1	75	163		
Bed 2	78	172		
Bed 3	43	13		
Living room 1. fl	61	79		

Table 7: Thermal comfort for case 0

4.1.3 Daylight

In view of results from thermal comfort, the situation for Bed 3 is opposite. Now it is the worst performing room, and the only room that does not satisfy the criteria of 50 % of area to achieve $D_T = 2.4\%$. It can be observed that there may be a corralation between good performance in terms of thermal comfort leading to bad performance for daylighting.

	TEK 17	NS-EN 17037	
	$\overline{DF} = 2.0[\%]$	50 % of area $\geq D_T = 2.4[\%]$	95 % of area $\geq D_{TM} = 0.8[\%]$
Kitchen	5.396	100	100
Dining room	5.722	100	100
Living room g.fl	5.568	98.2	100
Bed 1	3.853	97.2	100
Bed 2	2.914	52.2	100
Bed 3	2.586	35.3	100
Living room 1. fl	4.251	63.4	100

Table 8: Daylight provision for critical rooms in case 0

4.2 Case 1 - Rotated 90 degrees counter-clockwise

4.2.1 Energy

By orienting the building 90 degrees counter-clockwise, there is an interesting observation regarding how the different software interpret the energy performance. IDA ICE calculates a slightly lower annual heating demand, PHPP increases their value, while TEK-sjekk remains approximately the same. The change of orientation has caused the window share to the north to increase from $6.9m^2$ to $17.3m^2$. Looking at figure 16 and 17, one can observe the severe transmission loss increase for the north orientation. The decrease for east and west are to small to compensate for the impact from north. In the original case only living room in both floors and bedroom 1 was facing south. For this case, dining room, kitchen, living room ground floor, bedroom 1 and 2 has windows against south. Since IDA ICE calculates the rooms as individual zones the contribution of solar heat gain may influence the room temperature, which influence the need for space heating.

Software	**Annual heating demand** $[kWh/m^2]$
IDA-ICE	42.9 - 2.3%
PHPP	49.0 + 5.4%
TEK-sjekk	47.8 - 0.4%

Table 9: Heating demand for case 1

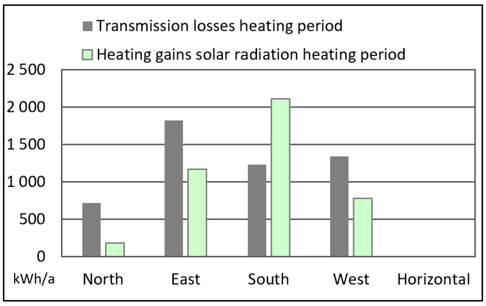


Figure 16: Solar heat gain case 0

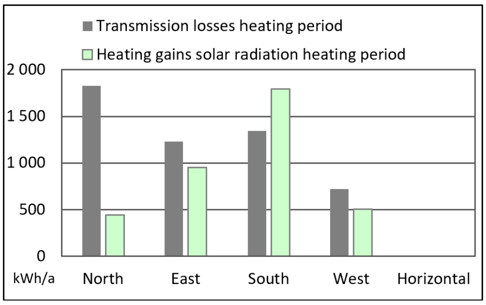


Figure 17: Solar heat gain case 1

4.2.2 Thermal comfort

The overall thermal comfort performance of the building has improved when oriented. Even though only the dining room performs worse than the reference case, neither IDA ICE or TEK-sjekk indicate that the thermal comfort performance fulfills criteria defined in TEK17 of maximum 50 hours. As observed in section 4.2.1, PHPP evaluates the building to have greater transmission losses, which correlate to why the frequency of overheating reduces for simulation performed in PHPP.

	IDA-ICE		PHPP	TEK-Sjekk
	Hours exceeding 26 degrees [h]	Unacceptable hours (IV)[h]	Frequency of overheating [%]	Hours exceeding 26 degrees [h]
Kitchen	61	44	0,3 % $\approx 26h$	78
Dining room	86	69		
Living room g.fl	49	28		
Bed 1	55	65		
Bed 2	65	91		
Bed 3	35	10		
Living room 1. fl	45	46		

Table 10: Thermal comfort for case 1

4.2.3 Daylight

By the definition of how the sky model "overcast sky" operate, there should be no change in daylight factor when rotating the building. The intention was therefore not to include the daylight results. Despite this, there are some notable differences. Bedroom 2 does not fulfil criterion for $D_T = 2.4\%$ from NS-EN 17037. Case 1 is only a revision of case 0, so the only deviation from the simulation file for case 0 is the orientation of the building model. Since there hasn't been simulated for different climate files, the possibility of there being a flaw in used climate file has not been investigated.

	TEK 17	NS-EN 17037	
	$\overline{DF} = 2.0[\%]$	50 % of area $\geq D_T = 2.4[\%]$	95 % of area $\geq D_{TM} = 0.8[\%]$
Kitchen	5.418	100	100
Dining room	5.722	100	100
Living room g.fl	5.568	98.0	100
Bed 1	3.381	86.6	100
Bed 2	2.578	41.5	100
Bed 3	2.585	35.3	100
Living room 1. fl	4.179	61.6	100

Table 11: Daylight provision for critical rooms in case 1

4.3 Case 2 - Improved building envelope

4.3.1 Energy

As expected, a more insulated wall decreases the annual heating demand. The same tendency as case 0 and 1 is shown here. IDA ICE calculates the lowest value of all softwares. On average there is a decrease of 27% in annual heating demand for all the softwares. This gives a quite significant performance increase for the building.

Software	**Annual heating demand** $[kWh/m^2]$
IDA-ICE	32.2 - 26.7%
PHPP	35.4 - 23.9%
TEK-sjekk	33.6 - 29.4%

Table 12: Heating demand for case 2

4.3.2 Thermal comfort

In terms of thermal comfort, this case performs similar to the original. Overall there is a slight increase of overheating, but nothing changes regarding fulfillment of criteria.

	IDA-ICE		PHPP	TEK-Sjekk
	Hours exceeding 26 degrees [h]	Unacceptable hours (IV)[h]	Frequency of overheating [%]	Hours exceeding 26 degrees [h]
Kitchen	77	64	0,5 % ≈ $44h$	93
Dining room	69	47		
Living room g.fl	78	82		
Bed 1	75	167		
Bed 2	78	194		
Bed 3	43	18		
Living room 1. fl	60	97		

Table 13: Thermal comfort for case 2

4.3.3 Daylight

The increase of wall thickness affects how much of the daylight that passes through the envelope. Table 14 shows that the daylight provision is worse for every room. The increased wall thickness is not enough to disapprove the criterion from TEK17. Bedroom 2 and 3 are the worst performing rooms. It is worth noticing that the other rooms still has some buffer before the values get below the criteria.

	TEK 17	NS-EN 17037	
	$\overline{DF} = 2.0[\%]$	50 % of area $\geq D_T = 2.4[\%]$	95 % of area $\geq D_{TM} = 0.8[\%]$
Kitchen	4.382	100	100
Dining room	4.702	100	100
Living room g.fl	4.708	92.8	100
Bed 1	3.144	86.1	100
Bed 2	2.420	38.7	100
Bed 3	2.145	27.7	100
Living room 1. fl	3.539	53.6	100

Table 14: Daylight provision for critical rooms in case 2

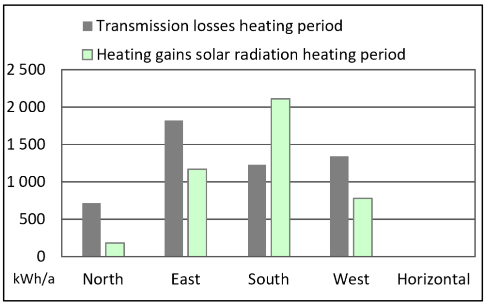
4.4 Case 3 - Maximum accepted obstructing shading object TEK17

4.4.1 Energy

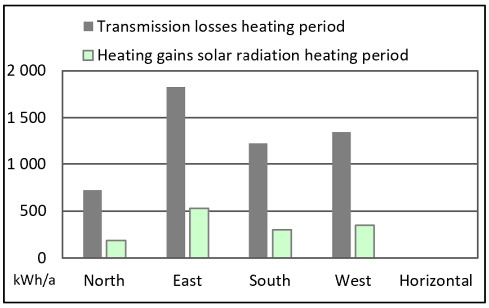
Because the nearby obstructions casts shadows on the building, the amount of solar radiation that hits the building reduces. This results in higher heating demand as presented in table 15. In figure 18 one can observe that the amount of heat gains due to solar radiation has reduced drastically. PHPP deviates from the other softwares with a much larger increase of 37 %.

Software	Annual heating demand $[kWh/m^2]$
IDA-ICE	55.1 + 25.1%
PHPP	63.7 + 37.0%
TEK-sjekk	57.0 + 19.7%

Table 15: Heating demand for case 3



(a) Solar heat gain case 0



(b) Solar heat gain case 3

Figure 18: Comparison of transmission loss and solar heat gain for case 0 and case 3

4.4.2 Thermal comfort

With this design, PHPP calculates that there would be no hours that exceed 26 degrees. IDA ICE still disapproves some of the rooms, but does not deviate too much from fulfillment. TEK-sjekk gives 31 hours of overheating compared to 92 in case 0. As for the latter, this is the first case it approves the risk of overheating.

	IDA-ICE		PHPP	TEK-Sjekk
	Hours exceeding 26 degrees [h]	Unacceptable hours (IV)[h]	Frequency of overheating [%]	Hours exceeding 26 degrees [h]
Kitchen	45	8	$0.0\ \% \approx 0h$	31
Dining room	46	6		
Living room g.fl	47	19		
Bed 1	57	57		
Bed 2	59	57		
Bed 3	37	9		
Living room 1. fl	53	36		

Table 16: Thermal comfort for case 3

4.4.3 Daylight

Bedroom 3 is here just on the edge of being approved for TEK17. According to NS-EN 17037, none of the requirements are met. Since this room is so affected by the obstruction, a similar scenario for this facade should be avoided. It is important to keep in mind that this quality still is approved by the simplified method in TEK17.

	TEK 17	NS-EN 17037	
	$\overline{DF} = 2.0[\%]$	50 % of area $\geq D_T = 2.4[\%]$	95 % of area $\geq D_{TM} = 0.8[\%]$
Kitchen	3.838	68.0	100
Dining room	4.592	97.1	100
Living room g.fl	3.456	49.8	100
Bed 1	3.052	65.6	100
Bed 2	2.405	36.1	100
Bed 3	2.040	25.6	77.3
Living room 1. fl	3.202	40.8	100

Table 17: Daylight provision for critical rooms in case 3

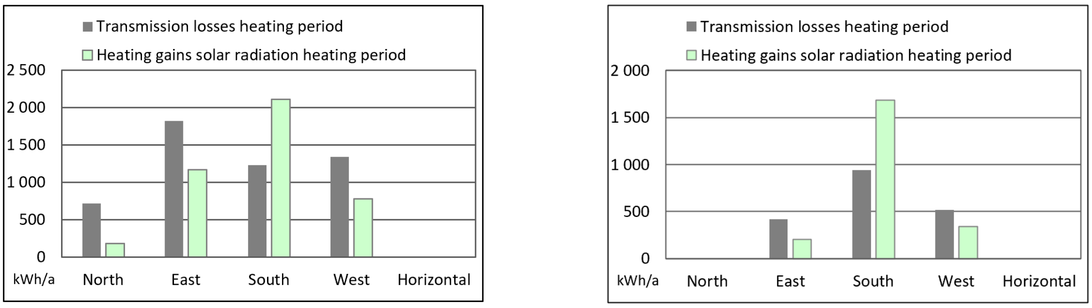
4.5 Case 4 - Minimum glazing criterion TEK17

4.5.1 Energy

This case simulates a case that is a bit different from the reference model. With the implementation of minimum allowed window area according to the simplified method in TEK17, the heat transfer through the windows should be affected by this. As indicated by figure 19 the values for each facade is smaller. The net heat gain is positive for case 4. This design gives savings in terms of energy needed for heating, as illustrated in table 18. TEK-Sjekk calculates the most energy saving compared to reference case, even though IDA ICE calculates the lowest annual heating demand.

Software	**Annual heating demand** $[kWh/m^2]$
IDA-ICE	36.2 - 17.5%
PHPP	38.7 - 16.8%
TEK-sjekk	37.0 - 22.3%

Table 18: Heating demand for case 4



(a) Solar heat gain case 0

(b) Solar heat gain case 4

Figure 19: Comparison of transmission loss and solar heat gain for case 0 and case 4

4.5.2 Thermal comfort

Overall this case performs very good with respect to the thermal comfort criteria. IDA ICE approves thermal comfort for every room except Bedroom 2. The amount of unacceptable hours are still high for this room, but within acceptable limits for NS-EN 16798-1:2019. It is the largest rooms that performs the best, with kitchen, dining room and the living room on ground floor having just 2 unacceptable hours. PHPP calculates that there will be no frequency of overheating.

	IDA-ICE		PHPP	TEK-Sjekk
	Hours exceeding 26 degrees [h]	Unacceptable hours (IV)[h]	Frequency of overheating [%]	Hours exceeding 26 degrees [h]
Kitchen	31	2		
Dining room	29	2		
Living room g.fl	32	2		
Bed 1	47	79	0.0 % $\approx 0h$	25
Bed 2	58	117		
Bed 3	25	8		
Living room 1. fl	44	31		

Table 19: Thermal comfort for case 4

4.5.3 Daylight

As expected based on the tendency from the previous cases, the overall daylight performance is very poor. None of the rooms fulfills the other criteria. A window design like this proves to be favorable in terms of energy and thermal comfort. It is still an unusual design, but it is worrying that the simplified method in TEK 17 still would have approved this solution.

	TEK 17	NS-EN 17037	
	$\overline{DF} = 2.0[\%]$	50 % of area $\geq D_T = 2.4[\%]$	95 % of area $\geq D_{TM} = 0.8[\%]$
Kitchen	1.549	15.4	93.7
Dining room	1.792	18.1	80.0
Living room g.fl	1.798	19.1	74.1
Bed 1	1.726	18.1	84.4
Bed 2	1.543	15.1	94.7
Bed 3	1.630	19.0	69.3
Living room 1. fl	1.729	20.7	65.4

Table 20: Daylight provision for critical rooms in case 4

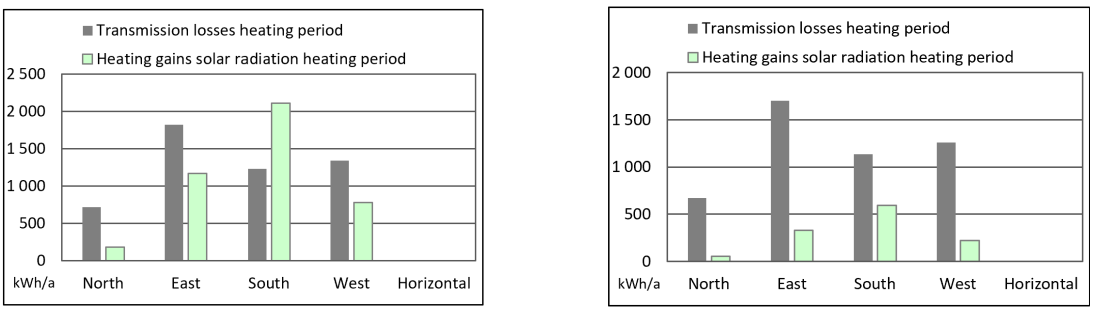
4.6 Case 5 - LT: 27 and g-factor: 16

4.6.1 Energy

This solution has very low g-factor with glazing properties similar to Pilkington 30/16. Due to this fact the solar heat gain has reduced as displayed in figure 20. The annual heating demand has therefore risen and has the worst performing energy results of the simulated cases.

Software	Annual heating demand $[kWh/m^2]$
IDA-ICE	59.6 + 35.8%
PHPP	62.4 + 34.2%
TEK-sjekk	56.2 + 18.1%

Table 21: Heating demand for case 5



(a) Solar heat gain case 0

(b) Solar heat gain case 5

Figure 20: Comparison of transmission loss and solar heat gain for case 0 and case 5

4.6.2 Thermal comfort

All rooms have good indoor thermal comfort with great margin. With respect to the glazing properties and transmission losses in figure 20 it is no surprise that this solution has the best thermal comfort performance.

	IDA-ICE		PHPP	TEK-Sjekk
	Hours exceeding 26 degrees [h]	Unacceptable hours (IV)[h]	Frequency of overheating [%]	Hours exceeding 26 degrees [h]
Kitchen	26	0	0.0 % $\approx 0h$	14
Dining room	24	0		
Living room g.fl	25	0		
Bed 1	37	19		
Bed 2	39	20		
Bed 3	20	4		
Living room 1. fl	31	12		

Table 22: Thermal comfort for case 5

4.6.3 Daylight

Table 23 shows that glazing properties with low LT and g-factor will most likely not satisfy the daylight criteria both for TEK17 and NS-EN 17037. However, some of the rooms does not deviate much from acceptance for TEK17. It is an interesting observation that Kitchen, Dining room, Living room g.fl and Bed 1, still satisfy the 0.8% criterion. The transmitted daylight is therefore better distributed in the rooms. A factor that helps achieving this is by having light transmittance from two different walls.

	TEK 17	NS-EN 17037	
	$\overline{DF} = 2.0[\%]$	50 % of area $\geq D_T = 2.4[\%]$	95 % of area $\geq D_{TM} = 0.8[\%]$
Kitchen	1.844	17.8	100
Dining room	1.995	19.5	100
Living room g.fl	1.919	22.2	99.0
Bed 1	1.400	2.3	99.1
Bed 2	0.9827	0.0	54.9
Bed 3	0.8993	2.5	39.0
Living room 1. fl	1.919	14.7	64.3

Table 23: Daylight provision for critical rooms in case 5

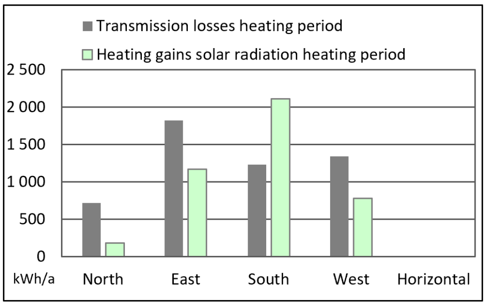
4.7 Case 6 - LT: 61 and g-factor: 33

4.7.1 Energy

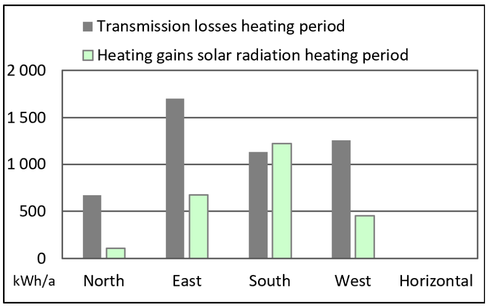
Case 6 has glazing properties similar to Pilkington 66/33. Due to the high increase of annual heating demand in previous case, this is a more preferable solution. Looking at table 24 TEK-Sjekk has again the smallest change from the reference model.

Software	Annual heating demand $[kWh/m^2]$
IDA-ICE	50.7 + 15.5%
PHPP	52.6 + 13.1%
TEK-sjekk	50.7 + 6.5%

Table 24: Heating demand for case 6



(a) Solar heat gain case 0



(b) Solar heat gain case 6

Figure 21: Comparison of transmission loss and solar heat gain for case 0 and case 6

4.7.2 Thermal comfort

In comparison to the reference case, an implementation of the glazing properties in this case is a required measure that could to satisfy the thermal comfort criteria. TEK-Sjekk still disapproves, but with only 3 hours over the limit. Case 6 is a more reasonable measure in Nordic climate than case 5.

	IDA-ICE		PHPP	TEK-Sjekk
	Hours exceeding 26 degrees [h]	Unacceptable hours (IV)[h]	Frequency of overheating [%]	Hours exceeding 26 degrees [h]
Kitchen	43	12	$0.0\ \% \approx 0h$	53
Dining room	42	7		
Living room g.fl	40	13		
Bed 1	52	67		
Bed 2	52	73		
Bed 3	29	7		
Living room 1. fl	44	33		

Table 25: Thermal comfort for case 6

4.7.3 Daylight

Bedroom 3 marginally satisfies the criterion in TEK17 with these glazing properties. On the other hand it does not meet the requirements in NS-EN 17037. This may be due to the fact that the maximum daylight factor is lowered because of the light transmittance of the glazing. Case 6 is a much more favorable variant than case 5 in terms of daylight performance.

	TEK 17	NS-EN 17037	
	$\overline{DF} = 2.0[\%]$	50 % of area $\geq D_T = 2.4[\%]$	95 % of area $\geq D_{TM} = 0.8[\%]$
Kitchen	4.118	96.5	100
Dining room	4.508	99.2	100
Living room g.fl	4.139	66.4	100
Bed 1	3.056	78.6	100
Bed 2	2.336	35.5	100
Bed 3	2.033	25.7	94.9
Living room 1. fl	3.361	47.4	100

Table 26: Daylight provision for critical rooms in case 6

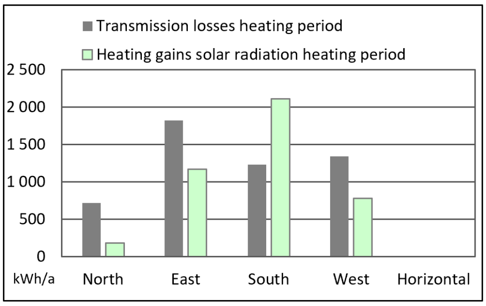
4.8 Case 7 - Revised window design

4.8.1 Energy

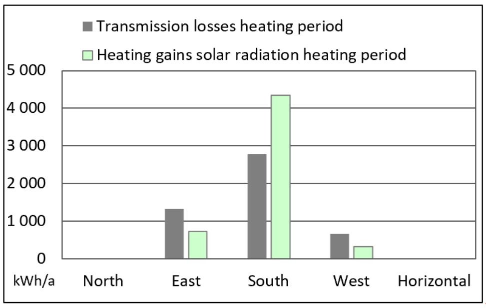
Looking at the results in table 29, a revised window design has large potential in terms of energy savings. IDA ICE and PHPP calculates a decrease of 17 % in annual heating demand, while TEK-Sjekk has a smaller profit, but is still significant. Figure 22 shows that the revised window design eliminates most of the transmission losses. Furthermore, the heating gains compensate for the remaining losses, resulting in a net positive balance.

Software	**Annual heating demand** $[kWh/m^2]$
IDA-ICE	36.4 - 17.1%
PHPP	38.6 - 17.0%
TEK-sjekk	40.9 - 14.1%

Table 27: Heating demand for case 7



(a) Solar heat gain case 0



(b) Solar heat gain case 7

Figure 22: Comparison of transmission loss and solar heat gain for case 0 and case 7

4.8.2 Thermal comfort

In comparison to the reference case, this case performs slightly better according to IDA ICE. More rooms are within acceptable range, where Bed 2 still has bad thermal comfort performance. Bed 1 does here satisfy criteria both in TEK17 and the adaptive method extracted from IDA ICE. Despite this, PHPP totally disagrees with these results. The frequency of overheating is 2.4 % which corresponds to 210 hours. This result is unusual compared to results in other cases. Since this case is based on a more comprehensive design change, this could be a possible source of error.

	IDA-ICE		PHPP	TEK-Sjekk
	Hours exceeding 26 degrees [h]	Unacceptable hours (IV)[h]	Frequency of overheating [%]	Hours exceeding 26 degrees [h]
Kitchen	55	26	$2.4\ \% \approx 210h$	95
Dining room	47	14		
Living room g.fl	56	61		
Bed 1	45	79		
Bed 2	63	136		
Bed 3	33	11		
Living room 1. fl	86	131		

Table 28: Thermal comfort for case 7

4.8.3 Daylight

As illustrated in table 29, every room satisfy every criteria for daylight. With respect to the criterion in TEK17, Dining room and Bedroom 3 has the lowest values, but are still approximately 75% over the set criterion.

	TEK 17	NS-EN 17037	
	$\overline{DF} = 2.0[\%]$	50 % of area $\geq D_T = 2.4[\%]$	95 % of area $\geq D_{TM} = 0.8[\%]$
Kitchen	4.079	93.4	100
Dining room	3.544	50.7	100
Living room g.fl	6.294	87.9	100
Bed 1	5.535	58.3	100
Bed 2	4.843	51.4	100
Bed 3	3.455	52.2	100
Living room 1. fl	5.641	92.9	100

Table 29: Daylight provision for critical rooms in case 7

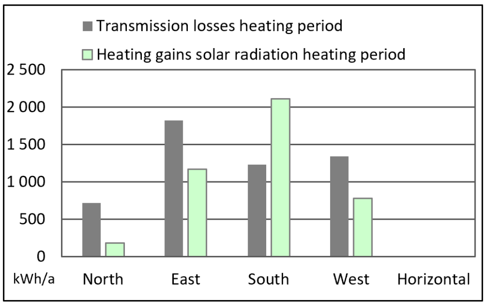
4.9 Case 8 - Static external overhang

4.9.1 Energy

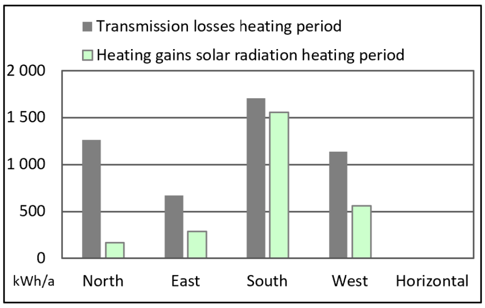
There is not much change in the energy performance by applying external overhang. Every software gives an increase of just above 3%. By studying the columns in figure 23, one can observe that the eastern and southern facade has the greatest impact. The northern facade has a big increase of transmission losses, so this solution should at least be avoided on this facade. The trend implies that if the case was a balcony overhang with a greater cantilever from the wall, the western facade is favorable for the studied building.

Software	Annual heating demand $[kWh/m^2]$
IDA-ICE	45.4 + 3.4%
PHPP	47.9 + 3.0%
TEK-sjekk	49.3 + 3.6%

Table 30: Heating demand for case 8



(a) Solar heat gain case 0



(b) Solar heat gain case 8

Figure 23: Comparison of transmission loss and solar heat gain for case 0 and case 7

4.9.2 Thermal comfort

The indoor thermal comfort is better for every room with an external overhang. Since the overhang is a nontransparent material, the shadowing effect proves to regulate the overheating risk due to solar radiation. The extracted results for the adaptive method in IDA ICE approves more or less every room.

	IDA-ICE		PHPP	TEK-Sjekk
	Hours exceeding 26 degrees [h]	Unacceptable hours (IV)[h]	Frequency of overheating [%]	Hours exceeding 26 degrees [h]
Kitchen	56	26		
Dining room	53	21		
Living room g.fl	50	43		
Bed 1	60	129	0.1 % $\approx 9h$	52
Bed 2	64	122		
Bed 3	32	10		
Living room 1. fl	46	54		

Table 31: Thermal comfort for case 8

4.9.3 Daylight

The external overhang does not seem to affect the D_{TM} criteria very much. This indicates that the minimum level of daylight, still is adequate. However, some rooms struggles to achieve enough area of $D_T = 2.4\%$. The same rooms which has insufficient daylight provision in other cases.

	TEK 17	NS-EN 17037	
	$\overline{DF} = 2.0[\%]$	50 % of area $\geq D_T = 2.4[\%]$	95 % of area $\geq D_{TM} = 0.8[\%]$
Kitchen	3.137	85.0	100
Dining room	3.378	94.3	100
Living room g.fl	3.476	73.7	100
Bed 1	2.471	43.5	100
Bed 2	2.080	26.6	100
Bed 3	1.686	17.3	99.2
Living room 1. fl	2.806	42.9	100

Table 32: Daylight provision for critical rooms in case 8

4.10 Case 9 - Light shelf (horizontal)

4.10.1 Energy

As mentioned earlier, only results from IDA ICE are included. A interesting observation is that the annual heating demand is reduced. Normally, one would assume that by applying this shelf should increase the heating demand, as they shade the sunlight. A possible explanation could be that the high reflectance causes the solar radiation to hit more area of the interior surface, which further increases the temperature. This is not investigated further in this thesis, so it is only an assumption.

Software	Annual heating demand $[kWh/m^2]$
IDA-ICE	42.6 - 3.0% - 3.7 PV-production

Table 33: Heating demand for case 9

4.10.2 Thermal comfort

There is only marginal effects when mounting light shelves on the windows. The living room on the ground floor and kitchen can be observed to improve the most. Table 35 shows that it is the adaptive method which is influenced the most by applying changes.

	IDA-ICE	
	Hours over 26 degrees [h]	Unacceptable hours (IV) (NS-EN 16798-1:2019) [h]
Kitchen	62	33
Dining room	66	32
Living room g.fl	50	48
Bed 1	74	155
Bed 2	77	164
Bed 3	43	14
Living room 1. fl	56	71

Table 34: Thermal comfort for case 9

4.10.3 Daylight

The light shelves does not only allow daylight to be distributed further into the room, they also shade near the windows and can help reduce the risk of glare. By comparing the results in table 8 and table 35 it can be observed that Bed 2 and Bed 3 in fact increases their daylight factor. The other rooms performs worse in this case. There seems to be a connection with the already poor performing rooms getting a positive contribution, while the already good performing rooms are negatively affected.

	TEK 17	NS-EN 17037	
	$\overline{DF} = 2.0[\%]$	50 % of area $\geq D_T = 2.4[\%]$	95 % of area $\geq D_{TM} = 0.8[\%]$
Kitchen	4.437	100	100
Dining room	5.140	100	100
Living room g.fl	4.459	95.3	100
Bed 1	3.845	97.3	100
Bed 2	2.943	53.2	100
Bed 3	2.608	35.9	100
Living room 1. fl	3.396	54.2	100

Table 35: Daylight provision for critical rooms in case 9

4.11 Case 10 - Light shelf (Rotated 10 degrees towards the sun)

4.11.1 Energy

As expected, the rotated light shelf has more PV-production which further confirms the findings in the study by Lee et al. (2021). Despite this, the resulting heating demand, if all the produced energy cover heating demand, is exactly the same as for the horizontal shelf in case 9.

Software	**Annual heating demand** $[kWh/m^2]$
IDA-ICE	43.7 - 0.5% - 4.8 PV-production

Table 36: Heating demand for case 10

4.11.2 Thermal comfort

Similar to case 9, there is not much effect on the thermal comfort. The rotated shelf does however give slightly better results, due to the increased obstructing surface. This make the living room on the ground floor satisfy the amount of overheating hours over 26 degrees.

	IDA-ICE	
	Hours over 26 degrees [h]	Unacceptable hours (IV) (NS-EN 16798-1:2019) [h]
Kitchen	55	34
Dining room	63	32
Living room g.fl	47	50
Bed 1	74	155
Bed 2	77	166
Bed 3	43	14
Living room 1. fl	62	70

Table 37: Thermal comfort for case 10

4.11.3 Daylight

Approximately the same results as for case 9. As described previously, the increased obstructing surface shades more of the indoor space, which results in slightly lower daylight values.

	TEK 17	NS-EN 17037	
	$\overline{DF} = 2.0[\%]$	50 % of area $\geq D_T = 2.4[\%]$	95 % of area $\geq D_{TM} = 0.8[\%]$
Kitchen	4.212	100	100
Dining room	4.997	100	100
Living room g.fl	4.197	90.1	100
Bed 1	3.828	97.3	100
Bed 2	2.925	52.3	100
Bed 3	2.598	35.7	100
Living room 1. fl	3.282	51.3	100

Table 38: Daylight provision for critical rooms in case 10

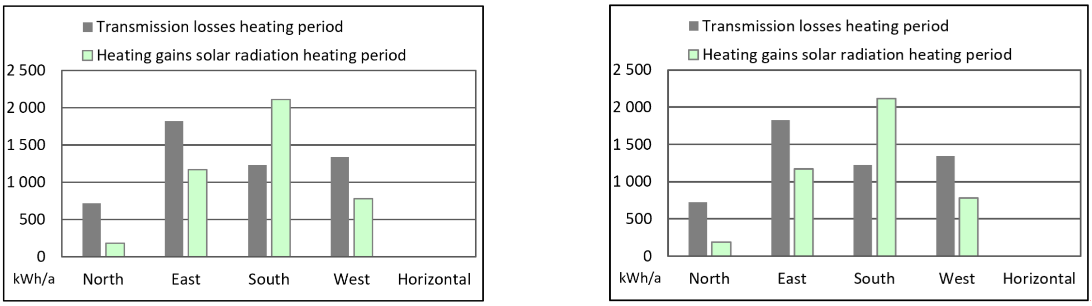
4.12 Case 11 - External shading

4.12.1 Energy

Surprisingly, changing to external blinds improves the energy performance. IDA ICE calculates a decrease of annual heating demand by 2.3% while TEK-Sjekk calculates a similar 1.9%. PHPP calculates no change in heating demand. To investegate this it was performed a test by changing reduction factor to 0%. There was still no change in annual heating demand. It is therefore to believe that changing shading device, does not influence the heating demand in PHPP. The change of shading strategy does neither influence the transmission loss or solar heat gains through the windows, as shown in figure 24

Software	**Annual heating demand** $[kWh/m^2]$
IDA-ICE	42.9 - 2.3%
PHPP	46.5 + 0.0%
TEK-sjekk	46.7 - 1.9%

Table 39: Heating demand for case 11



(a) Solar heat gain case 0

(b) Solar heat gain case 11

Figure 24: Comparison of transmission loss and solar heat gain for case 0 and case 11

4.12.2 Thermal comfort

Just by changing from internal blinds to external blinds, eliminates all overheating risk for the studied building. Based on the results from IDA ICE, the adaptive method seems to be very affected by applying a different shading strategy. For instance, bedroom 2 went from 172 unacceptable hours to 19 unacceptable hours. This is only 11% of the reference case. There is a consensus of every software regarding fulfillment of the requirements.

	IDA-ICE		PHPP	TEK-Sjekk
	Hours exceeding 26 degrees [h]	Unacceptable hours (IV)[h]	Frequency of overheating [%]	Hours exceeding 26 degrees [h]
Kitchen	20	2		
Dining room	18	1		
Living room g.fl	22	2		
Bed 1	35	16	0,0 % $\approx 0h$	30
Bed 2	34	19		
Bed 3	19	3		
Living room 1. fl	27	7		

Table 40: Thermal comfort for case 11

4.13 Evaluation of optimal packages of solutions

By studying the results for each case, there are some rooms which has recurring bad performance. In terms of thermal comfort, Bed 2 and living room on first floor are worst performing.

	IDA-ICE	
	Hours over 26 degrees [h]	Unacceptable hours (IV) (NS-EN 16798-1:2019) [h]
Kitchen	55	34
Dining room	63	32
Living room g.fl	47	50
Bed 1	74	155
Bed 2	77	166
Bed 3	43	14
Living room 1. fl	62	70

Table 41: Thermal comfort for case 10

It is important to note that every room and case still would have been satisfied by the simplified method for daylight in §13-7(2). For this thesis only a detached house has been studied. A detached house has completely different circumstances than a apartment block in more urban areas. It is therefore to believe that the potential consequences of using the simplified method are greater for an apartment block in dense built areas rather than a detached house located in sub-urban areas. The $D_T = 2.4$ criterion in NS-EN 17037 is consistently the strictest, where this criterion can indicate a non-satisfied situation while criteria in TEK17 and $D_{TM} = 0.8$ are fulfilled. Since $D_T = 2.4$ requires the highest level of daylight factor, it is to believe that it does not take as much modifications before the maximum daylight factor drops. In many cases, $D_{TM} = 0.8$ from NS-EN 17037 achieves a level of 100%. Similar to $D_T = 2.4$, this criterion assures that zones in the room does not reach critical low daylight levels. The average daylight factor does not easily identify if a niche in a room has poor daylight provision. The criterion in NS-EN 17037 does however recognize such situations.

Weakest rooms:
Thermal comfort: Bed 2 and Living 1. fl
Daylight: Bed 2 and Bed 3

In order to evaluate the optimal package of solutions, a mix of the most advantageous measures from the case study have been combined. Rarely did the individual results show that all criteria were met simultaneously. Therefore, the cases are strategically composed to achieve good performance for energy, thermal comfort and daylight.

The following measures are changed from the reference case:

Table 42: Applied changes to optimal case

Component	Reference case	Optimal case
Windows North [m^2]	6.8	0
Windows East [m^2]	17.1	10.8
Windows South [m^2]	12.0	26.5
Windows West [m^2]	11.8	6.4
Wall thickness [mm]	200	300
Normalized thermal bridge [$\frac{W}{mK}$]	0.05	0.03
Infiltration [h^{-1}]	1.0	0.6
Shading control	Internal blinds	External blinds

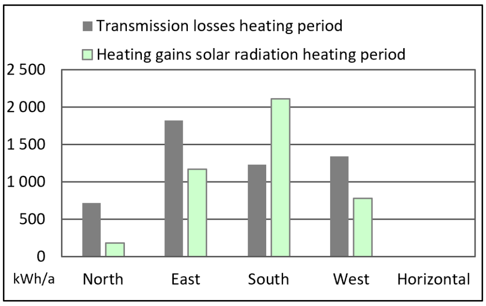
Case 2, improving building envelope, proved to decrease the annual heating demand but worsen the thermal comfort leading to more overheating hours. A revision of the window design in case 7, did enhance the daylight provision for every studied rooms as well as lowering the annual heating demand. Case 11, external window shading, did improve the thermal comfort drastically without much influence on the annual heating demand. It is therefore a logic measure to include. By assembling the cases directly, they counteract each other so that not all the requirements were met. To improve this, the thickness of the wall was changed from 350mm to 300mm in addition to the windows getting further optimizations. The height of the windows in the kitchen was reduced by 0,1m, and the window in Bed 2 is w:1,188m x h:1,388m rather than w:1,088m x h:1,288m in case 7.

4.13.1 Energy

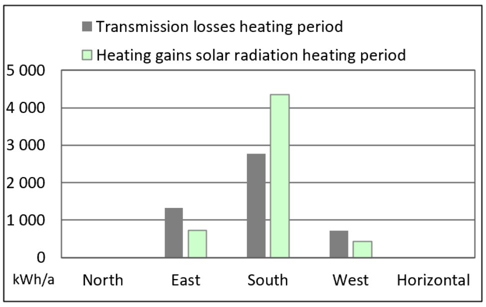
Even though the optimal case has less insulation in the wall, the combination with a revised window design gives overall a better performance than the investigated cases. PHPP calculates the greatest improvement, even though IDA ICE calculates largest decrease in annual heating demand for the individual cases of the combined ones. As illustrated in figure 25, the large heat gain from the south facade compensates for the greater transmission losses of the other facades. This is mostly due to the revised window design, with more windows oriented south, and a reduced amount on the other facades.

Software	Annual heating demand $[kWh/m^2]$
IDA-ICE	32.5 - 26.2%
PHPP	28.0 - 39.8%
TEK-sjekk	33.6 - 29.4%

Table 43: Heating demand for case optimal



(a) Solar heat gain case 0



(b) Solar heat gain case optimal

Figure 25: Comparison of transmission loss and solar heat gain for case 0 and case optimal

4.13.2 Thermal comfort

The results from PHPP has to be addressed first. Similar to case 7, revised window design, the frequency of overheating is very high. PHPP seems to be very dependent on the amount of solar radiation and from which facade. In most cases with a greater net transmission loss, the calculated overheating frequency is next to nothing. While for this case and case 7, which has increased glazing area to the south, are prone to more overheating. Otherwise, the thermal comfort criteria are satisfied both for overheating hours in TEK17, and unacceptable hours in the adaptive method.

	IDA-ICE		PHPP	TEK-Sjekk
	Hours exceeding 26 degrees [h]	Unacceptable hours (IV)[h]	Frequency of overheating [%]	Hours exceeding 26 degrees [h]
Kitchen	18	1		
Dining room	17	0		
Living room g.fl	22	2		
Bed 1	30	10	1.5 % ≈ 131h	15
Bed 2	33	31		
Bed 3	18	3		
Living room 1. fl	32	10		

Table 44: Thermal comfort for case optimal

4.13.3 Daylight

As illustrated in table 29, every room satisfy every criteria for daylight. With respect to the criterion in TEK17, Dining room and Bedroom 3 has the lowest values, but are still approximately 75% over the set criterion. The worst performing rooms in the case study, are here satisified, even with a buffer in terms of daylight factor criterion in TEK17.

	TEK 17	NS-EN 17037	
	$\overline{DF} = 2.0[\%]$	50 % of area $\geq D_T = 2.4[\%]$	95 % of area $\geq D_{TM} = 0.8[\%]$
Kitchen	3.154	61.9	100
Dining room	3.435	51.4	100
Living room g.fl	5.016	81.2	100
Bed 1	2.974	51.0	100
Bed 2	2.942	57.9	100
Bed 3	3.380	52.9	100
Living room 1. fl	4.912	87.5	100

Table 45: Daylight provision for critical rooms in case optimal

Chapter 5

Conclusion

By reviewing the results from the different cases, it is indicated that overheating and daylight can often give opposite results. Scenarios with good daylight provision can result in a poor thermal indoor environment.

When placing and orienting a building it is important to take into account the affect of obstructions in the horizon. Case 3 illustrates the maximum accepted obstruction, and heavily influence both the heating demand negatively, and daylight provision. These are permanent conditions, and there is therefore a risk of the building being permanently limited in its lifetime.

Since the daylight factor is calculated on a measuring plane with a height of 0,8m. Glazing areas below this height will therefore have a limited contribution on the calculated daylight factor. This also applies to the internal corners, where the daylight factor is calculated 0,5m from the internal wall perimeter. This is visualized for figures in apendix B.3 for the window closest to the kitchen in the living room on the ground floor. A revision of the window placement as in case 7, illustrates that there is large potential in in terms of annual heating demand, with a decrease of 14-17%. It can also satisfy every criteria for daylight. However, with a strategy of increasing the passive solar heat gain and limiting the transmission loss, there is a risk of overheating.

Changing the glazing properties did limit the risk of overheating. However, static glazing properties counteracts the desire to achieve good daylight performance and lowering the annual heating demand. Having different glazing properties for the most critical rooms for thermal comfort could be a solution. The static overhang in case 8, does regulate the overheating risk by some level, without fulfilling every criteria. Dynamic solutions such as applying external solar shading with control signal did eliminate the overheating risk of the studied building. Since the reference model is planned with internal blinds, it is to recommend that external blinds are implemented as a standard. At least for the most critical rooms in terms of thermal comfort.

Based on the results for thermal comfort, there is not always consistent outcome from the different softwares. A possible fault is that the model in IDA ICE is divided into several closed zones, so each individual room is not compatible to results for the entire building.

All the studied cases are constructed so that the simplified method for daylight in TEK17 are satisfied. The results in this thesis substantiate that there is a risk of residential buildings constructed according to the simplified method in TEK17 gives poor daylight performance. It must be noted that none of the studied cases represents the most extreme scenarios. A combination of the boundary conditions for case 3, maximum accepted obstructing shading object, and case 4, minimum glazing criterion, would illustrate an even worse scenario, which still would satisfy criteria regarding daylight in TEK17. Reviewing the daylight results for NS-EN 17037, the two criteria does control the level of daylight provision more than the average daylight factor in TEK17. The $D_T = 2.4$ criterion in NS-EN 17037 is consistently the strictest, where this criterion can indicate a non-satisfied situation while criteria in TEK17 and $D_{TM} = 0.8$ are fulfilled. A implementation of a additional criterion based on level of distribution similar to NS-EN 17037 is to recommend. It is more advantageous to include criterion similar to $D_T = 2.4$, since $D_{TM} = 0.8$ rarely deviate from results in average daylight factor.

Chapter 6

Future work

This master thesis investigates the relationship between annual heating demand, thermal comfort and daylight provision for a set of predefined cases for a single building. To give more robust and complete results more cases could have been applied and several building bodies should have been examined.

With the release of IDA ICE 5.0 it is possible to perform annual dynamic daylight simulations. It would be interesting to see how the results for annual daylight calculations compare to the results of daylight factor examined in this thesis. Furthermore the use of other simulation tools could provide more detailed daylight calculations as well as other methodologies for optimizing the building. Investigation of other types of shading devices would be interesting, and see how a dynamic simulation run calculates the daylight performance. With the correct plug-ins available the building geometry of the different softwares would be more equal, and the error reduced.

A further evaluation of the thermal comfort. Thermal comfort can be evaluated in several ways, and there is more guidelines and standards which are not considered in this thesis. This thesis focuses mainly on comparable criteria to the Norwegian regulations. More cases regarding different occupancy schedules could prove to give interesting results regarding the amount of overheating hours in the occupied hours.

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Appendix A

Original draft of scientific paper under review at Energies

Article

Optimalization of Window Design for Daylight and Thermal Comfort in Cold Climate Conditions

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Abstract: Window design affects the overall performance of the building. It is important to include window design during the initial stages of the project since it influences the performance of daylight, thermal comfort as well as energy demand for heating and cooling. The Norwegian building code facilitates two alternative methods for achieving sufficient daylight, and guidelines for adequate indoor thermal comfort. In this study, a typical Norwegian residential building has been modelled in IDA ICE to investigate how well the criteria and methods facilitate consistent and good performances through different scenario changes. Furthermore how the national regulations compare to European standards. A better insulated building has usually a lower annual heating demand, with only a marginal decrease in the daylight performance. At the same time, a tighter construction increases the risk of overheating even in cold climates. A revision of window design increases the overall performance of the building, which highlights the importance of good window design. The pursuit of lower energy demand should not be at expense of the indoor thermal comfort considering the anticipated future weather conditions. There should be paid more attention to which criteria that are reliable and should be used for daylight calculate, as this study indicate that the criteria in the national regulations and the European standards are not consistent.

Keywords: Energy optimization; Daylight; Thermal comfort; IDA ICE

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1. Introduction

Window design is an important aspect for the overall performance of the building. A unfortunate window design can overturn a high performance building to a building with poor performance. How this design is planned affects the energy efficiency in terms of both annual heating demand and cooling demand and the need for artificial lighting. The amount of solar radiation transmitting through the fenestration also affects the indoor thermal environment. Having sufficient daylight provision influences the visual comfort of the occupants. A good daylight design provides stimulating and well-lit indoor environments.

The solar radiation that hits the earth is equivalent to 15.000 times the total annual energy consumption for the entire earth. This solar energy can be utilized either in a passive or active form. Using the solar heat gains through windows for space heating, and the solar radiation as substitute for artificial lighting are examples of passive utilization [1]. Principles for active utilization could be solar thermal collectors that directly uses the solar energy to heat water that circuits the building for space heating and domestic hot water. Conversion of the solar energy to electricity in form of solar panels is also an example of active utilization [2]. Since Norway is an elongated country with various topography, the solar radiation is very dependent on location and season. Figure 1 illustrates the variation of solar irradiation in Norway for winter and summer conditions.

Figure 1. Daily solar irradiation on horizontal surface - January (left), July (right) [**?**].

Daylight ensures many qualities both for the indoor environment and the psychological well-being. Daylight openings provides connection to the outside while also illuminating the indoor surfaces. Many studies found that daylight has a positive influence on the human health and well-being. When the human skin is exposed to sunlight, it produces vitamin D which is linked to several health benefits [6]. Lansdowne et al. [7] found that the body also produces serotonin that helps improving the mood. A recent study discovers that a photoreceptor in the eye is sensitive to the wavelengths in the blue spectrum which daylight naturally covers, and synchronizes our internal biological clock [8].

While numerous other European countries specifies a minimum hours amount of solar exposure, the Norwegian government has decided to withdraw the paragraph concerning sunlight from the building code in the latest upgrade of the Norwegian technical requirements, TEK17 [9]. It is therefore imperative that the regulations define sufficient minimal criteria for the daylight provision. In 2019, the European daylight in buildings standard EN 17037 was implemented as a Norwegian standard. The standard encourages building designers to focus on providing sufficient daylight spaces, and also categorizes target ambitions with respect to daylighting [10].

Thermal comfort is an important parameter in building design and affects how the occupants appreciate the indoor environment. The occupant behaviour may have a direct impact on the buildings energy consumption. A critical aspect of thermal comfort is the risk of overheating. Since thermal comfort is a subjective condition it is hard to tell at which exact temperature overheating occurs. With the anticipated increase in temperature due to climate change, buildings in cold climates stand in front of a future with an increased risk for overheating during summer. Norway experienced a set of extreme heat waves in the summer of 2018 and 2019 [11]. Li et al. [12] did a study of the indoor overheating risk for converted lofts in London. One of their findings was that passive adaptations were not sufficient enough to eliminate the overheating, and it is likely that by the 2080s active cooling is a necessity. Tian and Hrynyszyn [13] found in their study thata retrofitting to higher energy standards and improving the airtightness, increases the risk of overheating, even in cold climates. They highlight that overheating should be paid more attention to based on the expected future climate conditions. Lee et al. [14] investigated how light shelves with applied photovoltaics could help maximizing the buildings energy efficiency. Light shelves rotated 10 degrees towards the sun proved to be most efficient in terms of PV-production during the summer conditions.

Norwegian residential buildings are regulated by TEK17. It is therefore most relevant to use the given performance criteria for daylight and thermal comfort in this regulation as a scale of measure. The aim of this paper is to investigate how well the criteria and methods facilitate a consistent and good performance in terms of daylight and thermal comfort. And also how the national regulations compare to European standard. The methodology of this study examines a set of parameter changes to an original case building. Each case is simulated in IDA ICE, and the results indicate how to optimize the design of the case building in terms of daylight and thermal comfort performance.

2. Background

2.1. Norwegian regulation

The Norwegian Building Regulations, TEK17, consist of a set of minimum properties and technical requirements that has to be satisfied in order to build legally. This building code defines functional regulations and performance criteria with attached pre-accepted performances which fulfill these requirements.

2.1.1. Thermal comfort

For thermal comfort there are two functional requirements which are relevant for design of residential dwellings. The following paragraphs are cited in TEK17:

§13-4 (1):

The thermal indoor climate in rooms intended for continuous occupancy shall be regulated in a manner that promotes health and satisfactory comfort when the rooms are used as intended

§13-4 (2):

In rooms for continuous occupancy it must be possible to open at least one external window or door

2.1.2. Daylight

TEK17 indicates two functional requirements that is considered to be relevant for building design. The following paragraphs are cited from TEK17[3].

§13-7 (1):

Construction works shall have adequate access to light

§13-7 (2):

Rooms for continuous occupancy shall have adequate access to daylight

The pre-accepted performances for §13-7 (2) give two methods for achieving required performance. The first method is based on the average daylight factor DF which has to be minimum 2.0% for the most critical rooms. Calculations with the use of simulations software have to validated according to CIE 171:2006 and the premises defined in NS-EN 12464-1:2011 chapter 4.4. The following equation needs to be fulfilled for selected rooms [3]:

$$\overline{DF} = 2.0\% \tag{1}$$

The premises from the European light standard NS-EN 12464-1:2011 describe how the grid systems shall be created. The maximum grid size is defined by the following equation [4]:

$$p = 0.2 \times 5^{log_{10}(d)} \tag{2}$$

Where:
p = Maximum grid size [m]
d = Longer dimension of the calculation area

Alternatively the daylight requirement can be achieved with a simplified simplified method [3]:

$$A_g \geq 0.07 \cdot A_{BRA} \cdot LT \tag{3}$$

Where:
A_g = Glazing area [m^2]
A_{BRA} = Usable floor space, including area of protruding building parts [m^2]
LT = Light transmittance of the glass [%]

2.2. *International regulations*

To compare the Norwegian regulations, a set of representative European standards are examined.

2.2.1. Thermal comfort

NS-EN 16798-1:2019 states that for defining the thermal environment, the criteria shall be based on the indices PMV-PPD from EN ISO 7730. For buildings without mechanical cooling the criteria could either be specified by the default method from EN ISO 7730, or by using the adaptive method. The adaptive method also considers the adaptation effects for occupant behavior when experiencing thermal discomfort. This method applies to buildings with sedentary activities where the occupant can adapt to the thermal conditions by either ventilating through windows or change of clothing. The collected data material is based on studies conducted in office buildings, but the standard ensures that the method also is applicable for similar spaces, such as residential buildings.

$$\Theta_{rm} = (\Theta_{ed-1} + 0,8\Theta_{ed-2} + 0,6\Theta_{ed-3} + 0,5\Theta_{ed-4} + 0,4\Theta_{ed-5} + 0,3\Theta_{ed-6} + 0,2\Theta_{ed-7})/3,8 \tag{4}$$

Table 1: Adaptive comfort temperatures categories for free running buildings [15]

Category I	upper limit	$\Theta_o = 0,33\Theta_{rm} + 18,8 + 2$
	lower limit	$\Theta_o = 0,33\Theta_{rm} + 18,8 - 3$
Category II	upper limit	$\Theta_o = 0,33\Theta_{rm} + 18,8 + 3$
	lower limit	$\Theta_o = 0,33\Theta_{rm} + 18,8 - 4$
Category III	upper limit	$\Theta_o = 0,33\Theta_{rm} + 18,8 + 4$
	lower limit	$\Theta_o = 0,33\Theta_{rm} + 18,8 - 5$

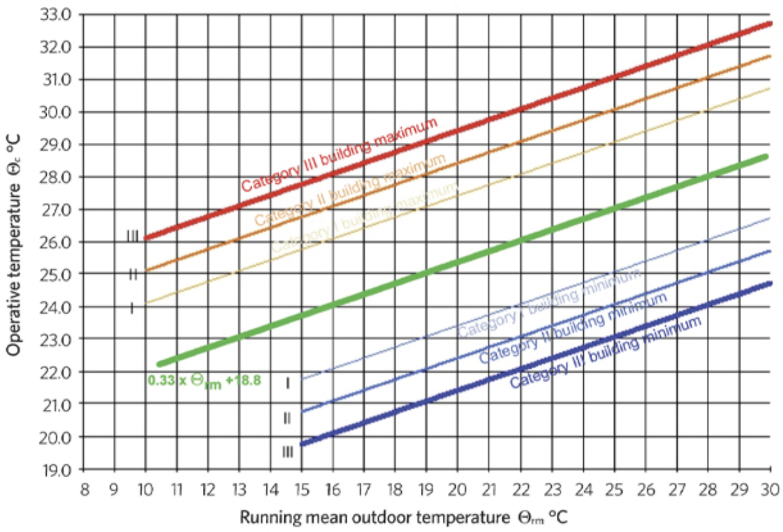

Figure 2. Acceptable operative temperature ranges based on temperatures from table 1 [16]

2.2.2. Daylight

The European standard for daylight in Buildings EN 17037:2018 is researched and prepared by Technical Committee CEN/TC 169 "Light and Lighting". The purpose of this paper is to facilitate a platform to secure adequate daylight provision in building design. The recommendations are categorized in different ambition levels as well as addressing challenging interfaces against view out, glare and exposure to sunlight. The standard was verified as a Norwegian Standard in February 2019. Since it has authority as a Norwegian Standard it will be referred to as NS-EN 17037:2018 further in this article.

Table A.1 — Recommendations of daylight provision by daylight openings in vertical and inclined surface

Level of recommendation for vertical and inclined daylight opening	**Target illuminance** E_T lx	**Fraction of space for target level** $F_{plane,\%}$	**Minimum target illuminance** E_{TM} lx	**Fraction of space for minimum target level** $F_{plane,\%}$	**Fraction of daylight hours** $F_{time,\%}$
Minimum	300	50 %	100	95 %	50 %
Medium	500	50 %	300	95 %	50 %
High	750	50 %	500	95 %	50 %

NOTE Table A.3 gives target daylight factor (D_T) and minimum target daylight factor (D_{TM}) corresponding to target illuminance level and minimum target illuminance, respectively, for the CEN capital cities.

Figure 3. Recommended values for daylight provision

The table shown in figure 3 from the standard gives recommended values based on desired level of ambition. The values for measurement is expressed in terms of illuminance measured in lux. Table A.3 in figure 4 gives corresponding daylight factor values for respective CEN capital cities.

Nation	**Capital** [a]	**Geographical latitude** φ [°]	**Median External Diffuse Illuminance** $E_{v,d,med}$	***D* to exceed 100 lx**	***D* to exceed 300 lx**	***D* to exceed 500 lx**	***D* to exceed 750 lx**
Norway	Oslo	59,90	12 400	0,8 %	2,4 %	4,0 %	6,0 %

Figure 4. Recommended values for daylight provision

3. Materials and Methods

3.1. Reference model

In this study a typical Norwegian residential building has been studied. Figure 5 displays a representative house model designed by Norgeshus. The total floor area is 140 m^2 over two floors. Common areas such as kitchen, dining area and living room are located on the ground floor, while bedrooms are situated on the first floor. See figure 6 for layout of the ground floor and figure 7 for the first floor.

Figure 5. Case building representing a typical residential building in Norway (Source: Norgeshus)

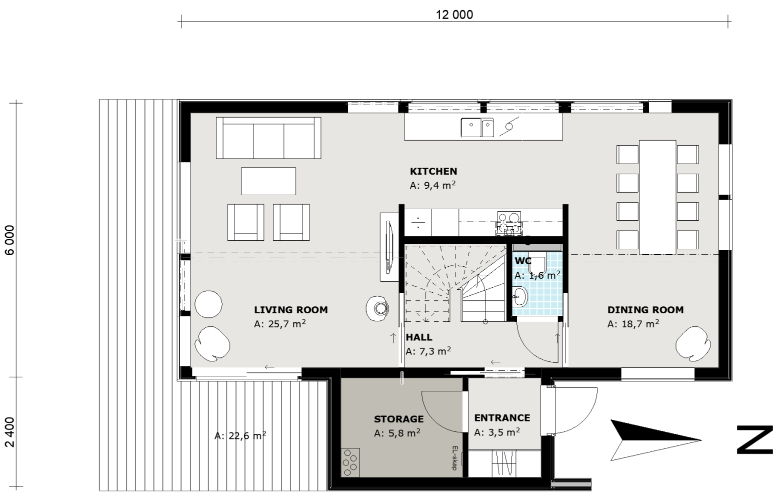

Figure 6. Ground floor layout (Source: Norgeshus)

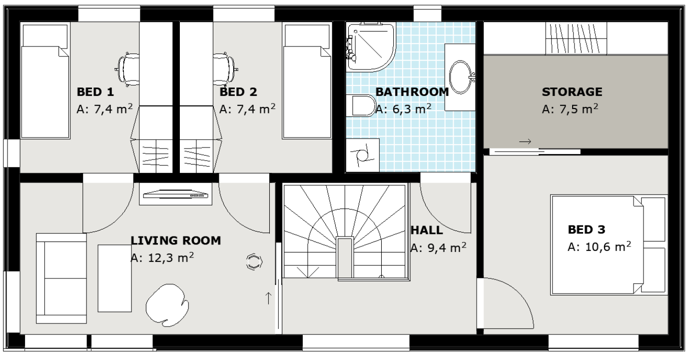

Figure 7. First floor layout (Source: Norgeshus)

The reference model is created with energy measures listed in table 2

Table 2: Input values regarding the building body for reference model

Input parameter	**Values for reference case**
U-value exterior walls (200mm)	0.198 W/m^2K
U-value roof	0.127 W/m^2K
U-value floor	0.094 W/m^2K
U-value windows and doors	0.900 W/m^2K
Window and door ratio of usable space	36 %
Temperature efficiency of heat recovery	80 %
Air leakage rate per hour at 50 Pa pressure difference	1.0 h^{-1}
Normalized thermal bridge	0.05 W/m^2K

Internal gains from occupants, equipments and lighting are defined according to the values set in the Norwegian technical standard, SN-NSPEK 3031:2020 [17].The deterministic occupancy schedule is based on schedules from Nord et al. [18] and adapted to fit the annual normalized values in the standard. By default, the reference model is applied with internal blinds that are PI-controlled with activation when operative indoor temperature reaches 23 °C. Windows open when operative temperature exceeds 25 °C.

3.2. Software

The building performance simulations were conducted by using the software IDA-ICE [19]. For the case study, IFC-models from ArchiCAD were imported to IDA-ICE with slight modifications through SimpleBIM. SimpleBIM has an add-on which addresses compatibility issues with IDA-ICE and enables the possibility of modifying the model to be validated for usage in IDA-ICE.

The daylight calculations were executed with the integrated Radiance simulation tool [20]. In order to facilitate results which are easily comparable to both Norwegian regulations and European standards, only the Daylight Factor (DF) has been examined. The daylight factor presumes the illumination on a horizontal reference plane in the room expressed in percentage of the simultaneous illumination on an outdoor horizontal plane with no casting shadows [21]. This is a simpler approach than a dynamic, climate derived illuminance calculation. The DF method is calculated for a CIE overcast sky, and is therefore independent on window orientation. For this sky model the luminance changes with altitude and is three times as bright at zenith than near the horizon [22]. Even though this method does not comply with the actual daylight environment, it still represents the unfavourable case and will unlikely give results better than actual daylight performance [23].

As previously mentioned, TEK17 gives two functional requirements for thermal comfort. The guidance for fulfilment of the functional requirement states that the performance is adequate if the exceedance of highest temperature does not surpass 50 hours in a normal year. The acceptance criterion for NS 16798 is based on CIBSE TM52, where the limit of unacceptable hours is set to be 3% of occupancy hours [24]. In other words, based on used occupancy schedule this corresponds to a maximum of 86 hours for dayrooms and 125 hours for bedrooms.

3.3. Simulated cases

10 alternative cases are presented in table 3. Case 1 aims to investigate the effect of only changing the orientation of the building, which is relevant for a lot of building scenarios. This is done by orienting the longer facade to the south. A typical measure for pursuing better energy efficiency is improving the building envelope with more insulation. Thus, Case 2 investigates this scenario. Case 3 and 4 represents cases the boundary criteria that are allowed for the simplified method in §13-7(2) TEK17. Case 5, 6 and 8 investigates measures for solar control. Since the daylight factor is calculated for an overcast sky, the affect of having different shading strategies are neglected, since they don't influence the daylight calculation. A revised window design, case 7, aims to discover how strategically changing the window design affects the performance of the same building body. Case 9 and 10 investigate the effect of new technology based on discoveries from Lee et al. [14]. One of the findings was that an inclination of -10° have the most PV-production. Hence, the choice of two alternative cases for comparison. For each case alternative, only mentioned parameter changes have been applied. The remaining model is equivalent to the reference model.

Table 3: Overview of simulated cases

Case nr	Case name	Case description
Case 0	Reference model	Original model with default values
Case 1	Oriented	Building model is rotated 90 degrees counter-clockwise
Case 2	Thicker walls	Improving the building envelope. 350mm insulation in walls
Case 3	Shading object	Maximum accepted obstruction angle in the horizon for the simplified method in TEK17
Case 4	Minimum glazing area	Minimum glazing criterion for the simplified method in TEK17 for each room
Case 5	Low light transmittance	New glazing properties: LT = 27 and g-factor: 16
Case 6	Medium light transmittance	New glazing properties: LT = 61 and g-factor: 33
Case 7	Revised window design	Removal of windows facing north, and more windows facing south
Case 8	Static external overhang	External overhang with depth of 1m
Case 9	Light shelf with PV-module (horizontal)	Mounted on windows >1m wide
Case 10	Light shelf with PV-module (-10° inclination)	Mounted on windows >1m wide. Rotated 10° towards the sun.

4. Results

In the following section the simulation results are presented. Each case alternative is evaluated in terms of annual heating demand, daylight and thermal comfort. While energy is displayed collectively on a single table, daylight and thermal comfort are presented in representative tables and figures relevant for the studied rooms in the building.

4.1. Energy

The simulated heating demand is expressed as the total energy need for space heating including ventilation. As expected a more insulated wall in case 2 and reduction of window area in case 4, decreases the need for annual heating. A decrease of almost 27% for case 2 is a quite significant performance increase for the building. Just by optimizing the window design as in case 7, revised window design, there is a profit of 7.5 kWh/m^2 annually. The light shelves themselves does not influence the energy performance significantly, but there is an advantage in the production of electricity which can be utilized. The implementation of such an installment is rather based on a cost-benefit perspective.

Table 4: Heating demand for every case

Case number	Annual heating demand $[kWh/m^2]$
Case 0	43.9
Case 1	42.9
Case 2	32.2
Case 3	55.1
Case 4	36.2
Case 5	59.6
Case 6	50.7
Case 7	36.4
Case 8	45.4
Case 9	42.6 - 3.7 PV-production
Case 10	43.7 - 4.8 PV-production

4.2. Daylight

Based on the daylight results, bedroom 2 and 3 are the worst performing rooms. A possible reason for this can be that these rooms have a one-sided light transmittance, and the geometry of these rooms regulate how well the light is distributed. Case 4 and 5 have obvious issues with giving adequate daylight provision. Furthermore, it is worth noticing that case 4 is designed as a minimum defined by the simplified method in TEK17 and is not approved by any of the used criteria in this paper. A horizontal light shelf gets a slight decrease in daylight provision, but does not deviate from the reference case concerning criteria acceptance. The rotated light shelf, case 10, performs similar, but has more profit of PV-production.

The results for daylight are calculated for each individual room considered. The results are evaluated according to criteria set in TEK17 ($\overline{DF} = 2.0\%$) and NS-EN 17037(50 % of area $\geq D_T = 2.4\%$ and 95 % of area $\geq D_{TM} = 0.8\%$). The following figures display the results for each room with respect to mentioned criteria.

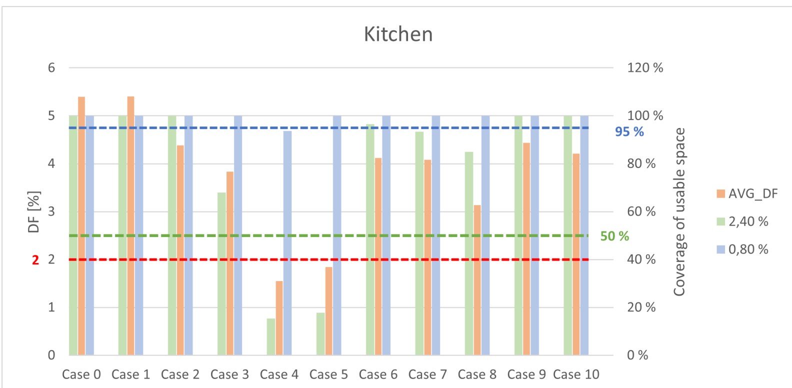

Figure 8. Simulation results for average daylight factor - Kitchen

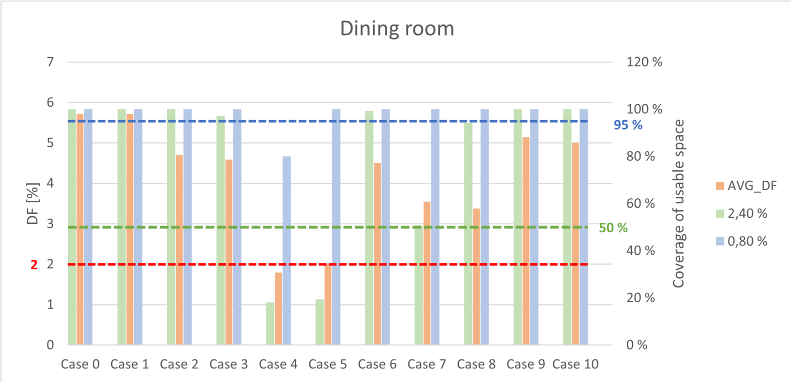

Figure 9. Simulation results for average daylight factor - Dining room

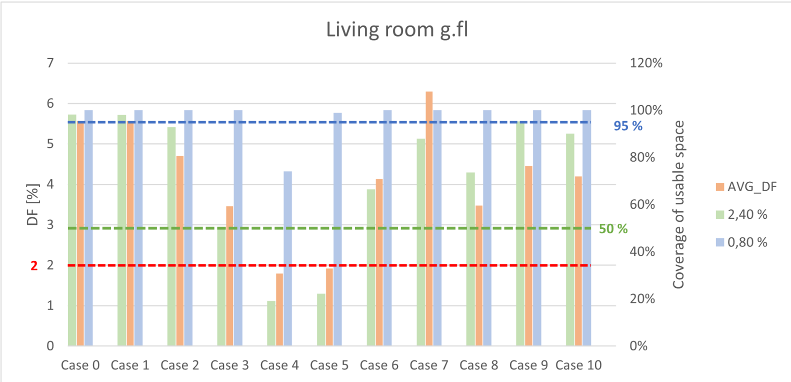

Figure 10. Simulation results for average daylight factor - Living room ground floor

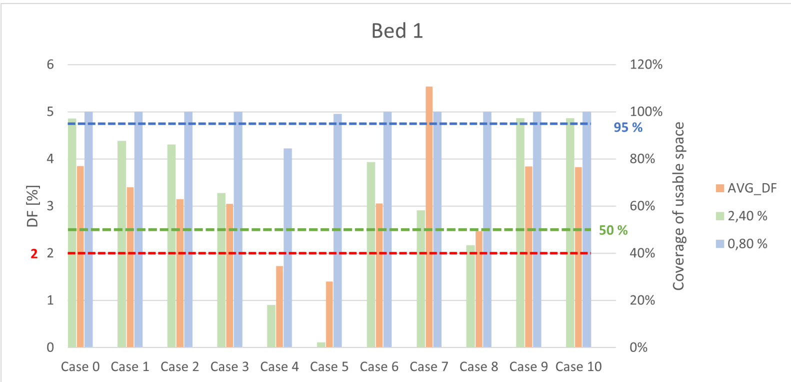

Figure 11. Simulation results for average daylight factor - Bed1

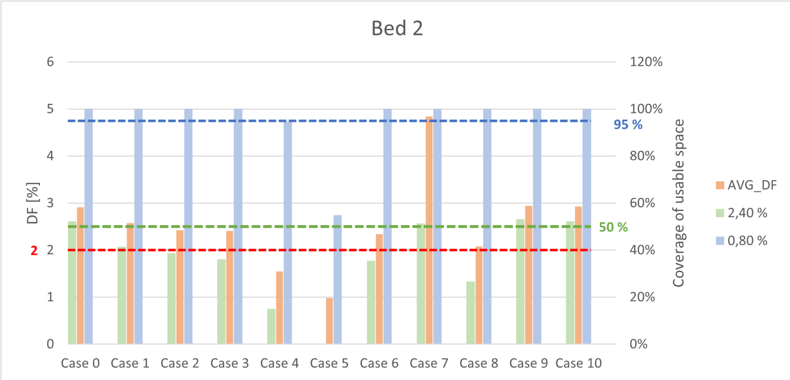

Figure 12. Simulation results for average daylight factor - Bed2

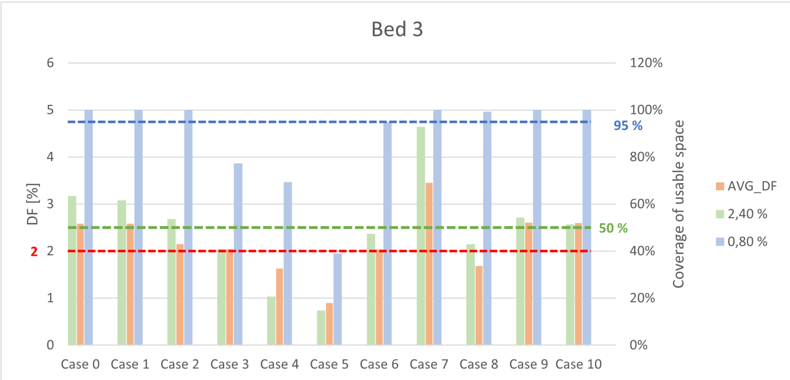

Figure 13. Simulation results for average daylight factor - Bed3

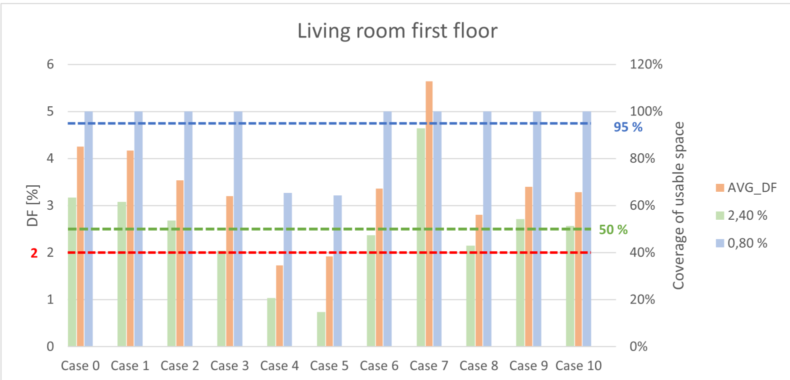

Figure 14. Simulation results for average daylight factor - Living room first floor

4.3. Thermal comfort

By default, the reference model does not satisfy the expected performance regarding overheating hours in TEK17, see figure 4.3. In contrast to the significant improvement for energy in case 2, thicker walls leads to more severe overheating risk, as illustrated in figure 4.3. Reduction of glazing area, case 4, or improving glazing properties tends to be the most effective. Case 6, medium light transmittance, is a more reasonable measure than case 5, low light transmittance, since the latter has poor performance both for energy and daylight. The revised window design in case 7, revised window design, has a slight overall improvement, but still is not satisfactory for bedroom 2 and the living room on first floor. Table 13 for case 8, static external overhang, shows that static external shading gives good results, and the disapproved rooms fails by a small margin. The light shelves do not influence the thermal comfort performance very much. For most of the cases, there is a correlation between good energy performance and bad thermal comfort performance and vice versa.

Case 0 - Reference model

Table 5: Thermal comfort for case 0

	IDA-ICE	
	Hours exceeding 26 °C [h]	Unacceptable hours (IV)[h]
Kitchen	67	53
Dining room	69	38
Living room g.fl	54	67
Bed 1	75	163
Bed 2	78	172
Bed 3	43	13
Living room 1. fl	61	79

Case 1 - Rotated 90 degrees counter-clockwise

Table 6: Thermal comfort for case 1

	IDA-ICE	
	Hours exceeding 26 °C [h]	Unacceptable hours (IV)[h]
Kitchen	61	44
Dining room	86	69
Living room g.fl	49	28
Bed 1	55	65
Bed 2	65	91
Bed 3	35	10
Living room 1. fl	45	46

Case 2 - Improved building envelope

Table 7: Thermal comfort for case 2

	IDA-ICE	
	Hours exceeding 26 °C [h]	Unacceptable hours (IV)[h]
Kitchen	77	64
Dining room	69	47
Living room g.fl	78	82
Bed 1	75	167
Bed 2	78	194
Bed 3	43	18
Living room 1. fl	60	97

256 **Case 3 - Maximum accepted obstructing shading object TEK17**

Table 8: Thermal comfort for case 3

	IDA-ICE	
	Hours exceeding 26 °C [h]	Unacceptable hours (IV)[h]
Kitchen	45	8
Dining room	46	6
Living room g.fl	47	19
Bed 1	57	57
Bed 2	59	57
Bed 3	37	9
Living room 1. fl	53	36

257 **Case 4 - Minimum glazing criterion TEK17**

Table 9: Thermal comfort for case 4

	IDA-ICE	
	Hours exceeding 26 °C [h]	Unacceptable hours (IV)[h]
Kitchen	31	2
Dining room	29	2
Living room g.fl	32	2
Bed 1	47	79
Bed 2	58	117
Bed 3	25	8
Living room 1. fl	44	31

Case 5 - LT: 27 and g-factor: 16

Table 10: Thermal comfort for case 5

	IDA-ICE	
	Hours exceeding 26 °C [h]	Unacceptable hours (IV)[h]
Kitchen	26	0
Dining room	24	0
Living room g.fl	25	0
Bed 1	37	19
Bed 2	39	20
Bed 3	20	4
Living room 1. fl	31	12

Case 6 - LT: 61 and g-factor: 33

Table 11: Thermal comfort for case 6

	IDA-ICE	
	Hours exceeding 26 °C [h]	Unacceptable hours (IV)[h]
Kitchen	43	12
Dining room	42	7
Living room g.fl	40	13
Bed 1	52	67
Bed 2	52	73
Bed 3	29	7
Living room 1. fl	44	33

260 **Case 7 - Revised window design**

Table 12: Thermal comfort for case 7

	IDA-ICE	
	Hours exceeding 26 °C [h]	Unacceptable hours (IV)[h]
Kitchen	55	26
Dining room	47	14
Living room g.fl	56	61
Bed 1	45	79
Bed 2	63	136
Bed 3	33	11
Living room 1. fl	86	131

261 **Case 8 - Static external overhang**

Table 13: Thermal comfort for case 8

	IDA-ICE	
	Hours exceeding 26 °C [h]	Unacceptable hours (IV)[h]
Kitchen	56	26
Dining room	53	21
Living room g.fl	50	43
Bed 1	60	129
Bed 2	64	122
Bed 3	32	10
Living room 1. fl	46	54

262 4.3.1. **Case 9 - Light shelf (horizontal)**

Table 14: Thermal comfort for case 9

	IDA-ICE	
	Hours over 26 °C [h]	Unacceptable hours (IV) [h]
Kitchen	62	33
Dining room	66	32
Living room g.fl	50	48
Bed 1	74	155
Bed 2	77	164
Bed 3	43	14
Living room 1. fl	56	71

263 **Case 10 - Light shelf (Rotated 10 degrees towards the sun)**

Table 15: Thermal comfort for case 10

	IDA-ICE	
	Hours over 26 °C [h]	Unacceptable hours (IV) [h]
Kitchen	55	34
Dining room	63	32
Living room g.fl	47	50
Bed 1	74	155
Bed 2	77	166
Bed 3	43	14
Living room 1. fl	62	70

5. Conclusions

Improving the building envelope is a recommended measure since it results in lower annual heating demand, and only has marginal loss in daylight performance. In terms of thermal comfort this scenario gives too large overheating risk, but in combination with either change of glazing properties or external shading has proved to be efficient. This highlights that well-insulated buildings has a risk of overheating even in cold climates, which further confirms the findings by Tian and Hrynyszyn [13]. The pursuit of lower energy demand should not be at expense of the indoor thermal comfort for the anticipated future weather conditions.

By performing a revision of the window design, the overall performance of the building improved. This indicates that daylight should be considered holistic already from the initial stages. By having window design in mind for the initial stages of planning, it can result, not only in better daylight provision, but also improved energy and thermal comfort performance, because they tie together.

There should be paid more attention to which criteria that are being used for daylight calculation, as the criteria are not consistent. According to the simulated results presented in this paper, the simplified method in TEK17 gives acceptance of a criteria which neither the average daylight factor or criteria in NS-EN 17037 approves. And a theoretical combination with case 3, maximum accepted obstruction, that also is accepted by the simplified method, would give an even worse daylight performance. A simplified method should be the most conservative alternative and give the oversized alternative while the advanced method should optimize closer to acceptable limit.

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Conflicts of Interest: The authors declare no conflict of interest.

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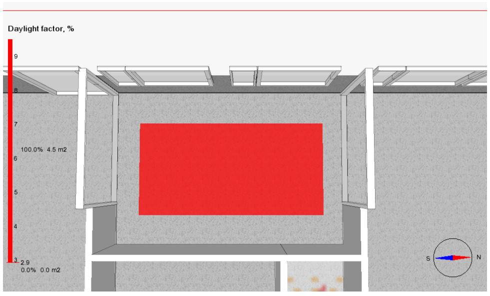
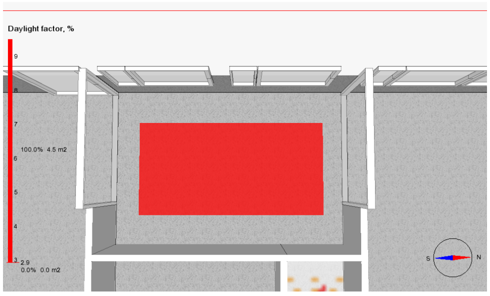
Vedlegg B

Daylight factor distribution - Plan view

B.1 Kitchen

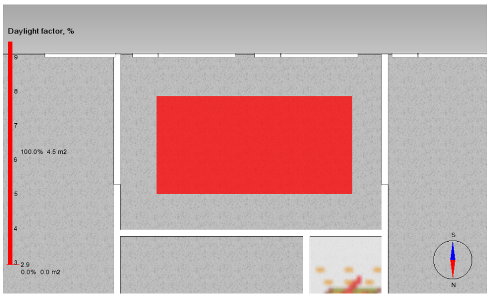


(a) Case0: $D_{TM} = 0.8$

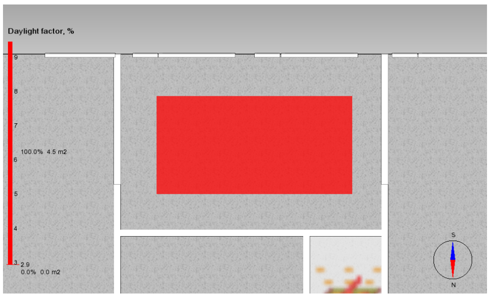


(b) Case0: $D_T = 2.4$

Figure 26: Daylight distribution in plan view for case 0 in kitchen

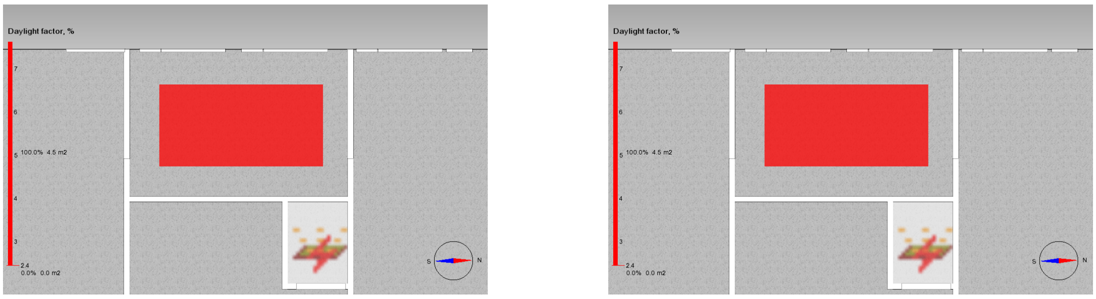


(a) Case1: $D_{TM} = 0.8$



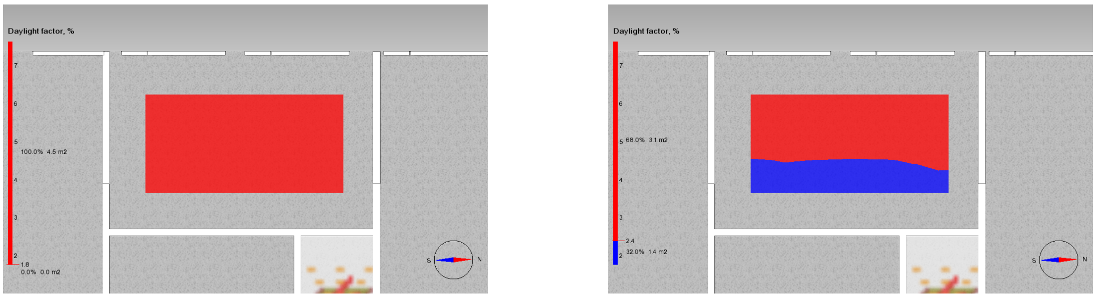
(b) Case1: $D_T = 2.4$

Figure 27: Daylight distribution in plan view for case 1 in kitchen



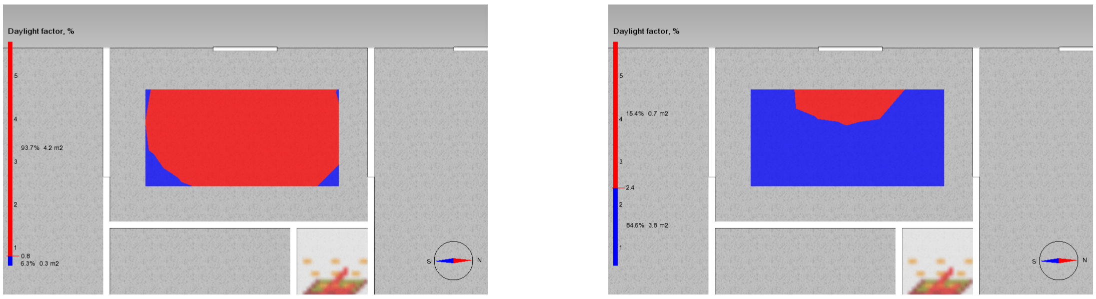
(a) Case2: $D_{TM} = 0.8$ (b) Case2: $D_T = 2.4$

Figure 28: Daylight distribution in plan view for case 2 in kitchen



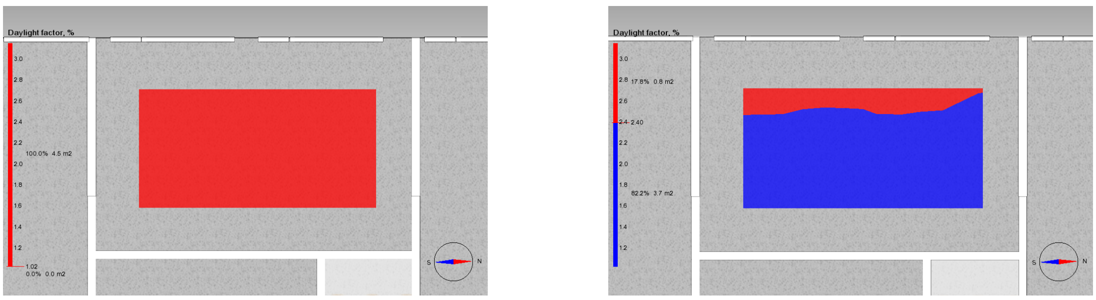
(a) Case3: $D_{TM} = 0.8$ (b) Case3: $D_T = 2.4$

Figure 29: Daylight distribution in plan view for case 3 in kitchen



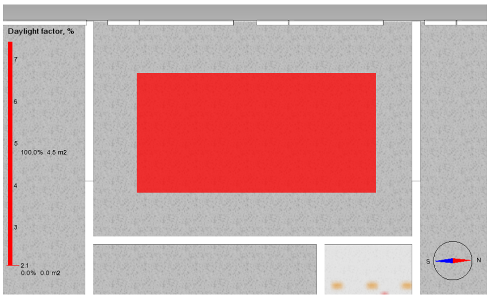
(a) Case4: $D_{TM} = 0.8$ (b) Case4: $D_T = 2.4$

Figure 30: Daylight distribution in plan view for case 4 in kitchen

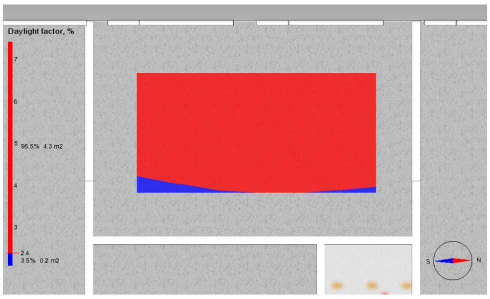


(a) Case5: $D_{TM} = 0.8$ (b) Case5: $D_T = 2.4$

Figure 31: Daylight distribution in plan view for case 5 in kitchen

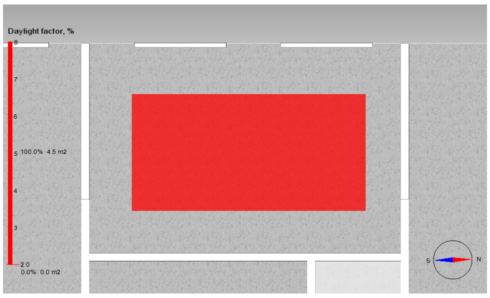


(a) Case6: $D_{TM} = 0.8$

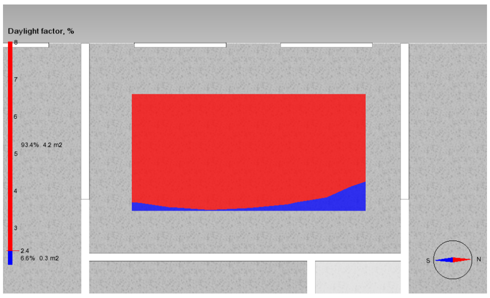


(b) Case6: $D_T = 2.4$

Figure 32: Daylight distribution in plan view for case 6 in kitchen

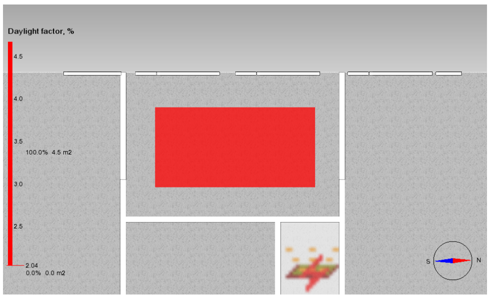


(a) Case7: $D_{TM} = 0.8$

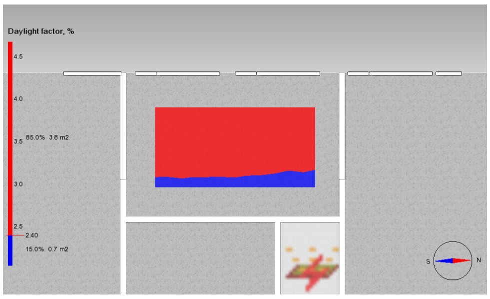


(b) Case7: $D_T = 2.4$

Figure 33: Daylight distribution in plan view for case 7 in kitchen

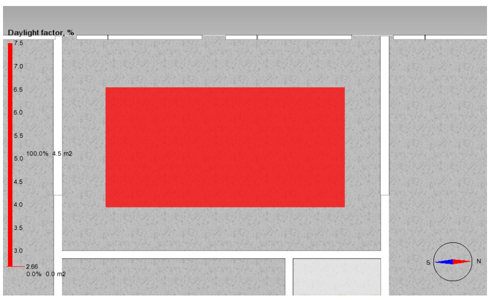


(a) Case8: $D_{TM} = 0.8$

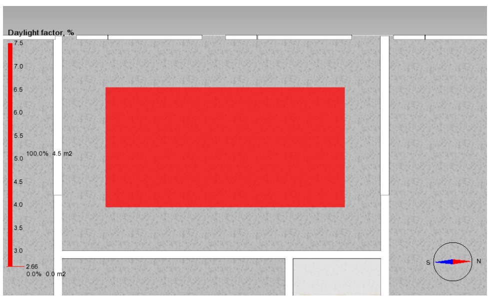


(b) Case8: $D_T = 2.4$

Figure 34: Daylight distribution in plan view for case 8 in kitchen

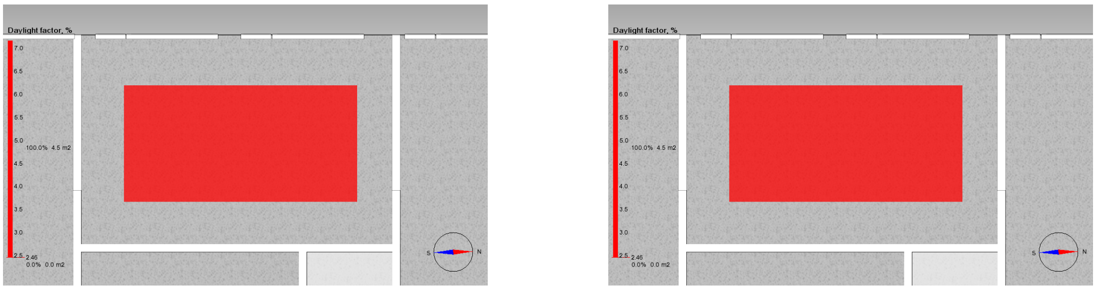


(a) Case9: $D_{TM} = 0.8$



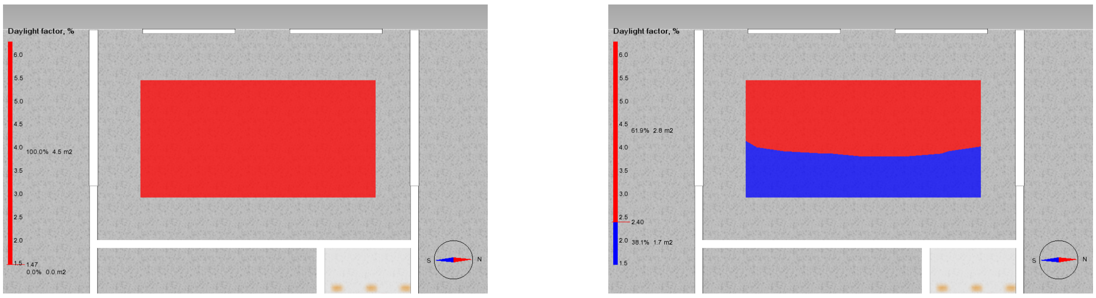
(b) Case9: $D_T = 2.4$

Figure 35: Daylight distribution in plan view for case 9 in kitchen



(a) Case10: $D_{TM} = 0.8$ (b) Case10: $D_T = 2.4$

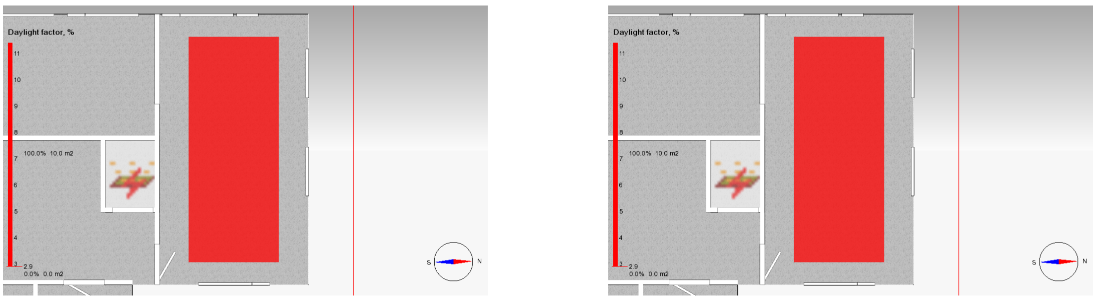
Figure 36: Daylight distribution in plan view for case 10 in kitchen



(a) Case optimal: $D_{TM} = 0.8$ (b) Case optimal: $D_T = 2.4$

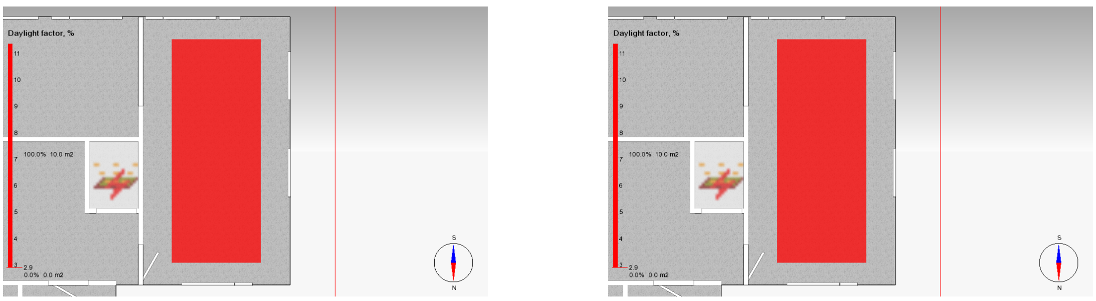
Figure 37: Daylight distribution in plan view for case optimal in kitchen

B.2 Dining room



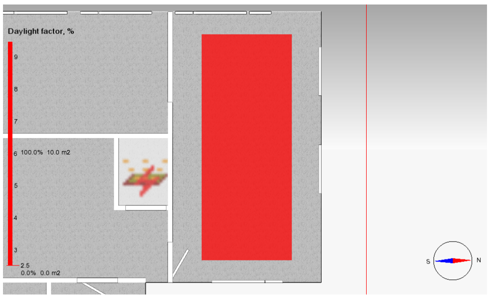
(a) Case0: $D_{TM} = 0.8$ (b) Case0: $D_T = 2.4$

Figure 38: Daylight distribution in plan view for case 0 in dining room

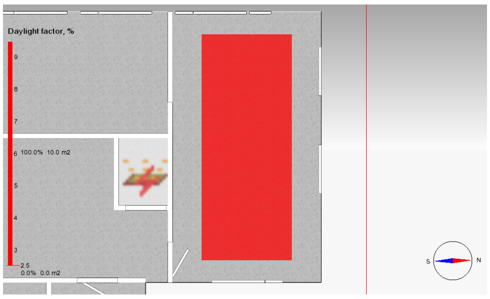


(a) Case1: $D_{TM} = 0.8$ (b) Case1: $D_T = 2.4$

Figure 39: Daylight distribution in plan view for case 1 in dining room

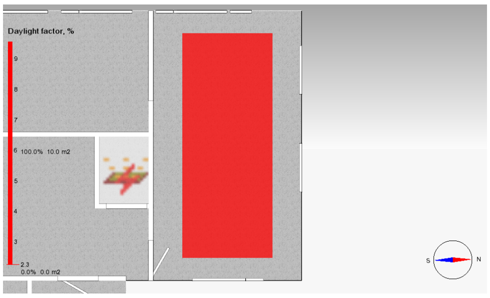


(a) Case2: $D_{TM} = 0.8$

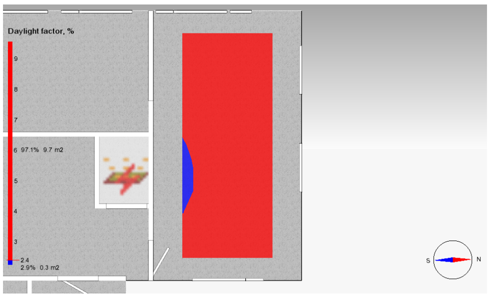


(b) Case2: $D_T = 2.4$

Figure 40: Daylight distribution in plan view for case 2 in dining room

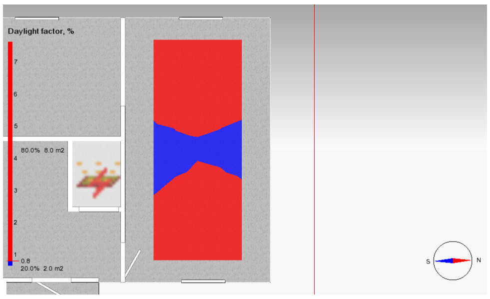


(a) Case3: $D_{TM} = 0.8$

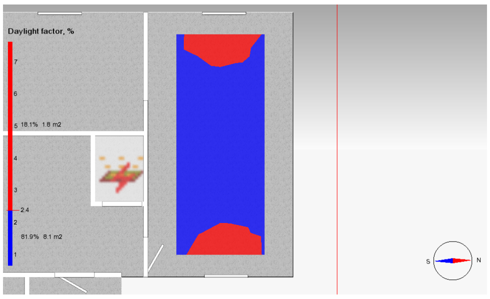


(b) Case3: $D_T = 2.4$

Figure 41: Daylight distribution in plan view for case 3 in dining room

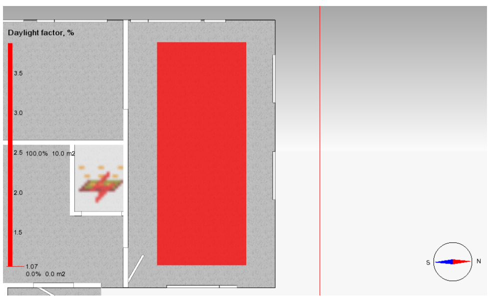


(a) Case4: $D_{TM} = 0.8$

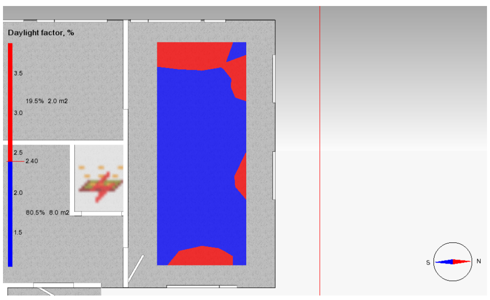


(b) Case4: $D_T = 2.4$

Figure 42: Daylight distribution in plan view for case 4 in dining room

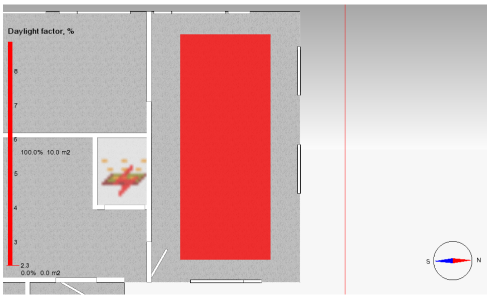


(a) Case5: $D_{TM} = 0.8$

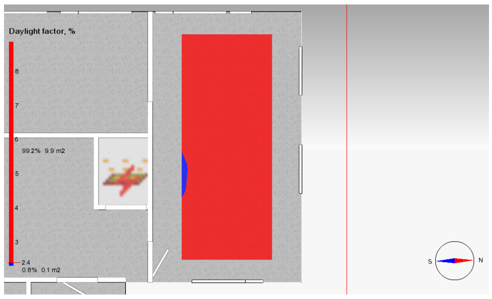


(b) Case5: $D_T = 2.4$

Figure 43: Daylight distribution in plan view for case 5 in dining room

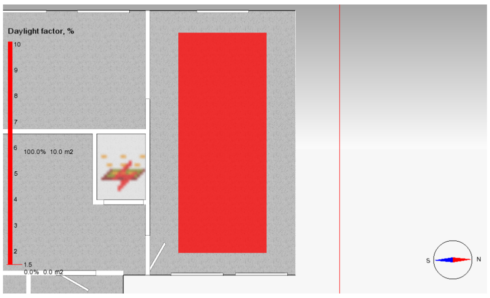


(a) Case6: $D_{TM} = 0.8$

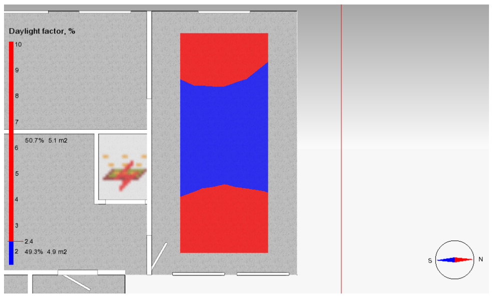


(b) Case6: $D_T = 2.4$

Figure 44: Daylight distribution in plan view for case 6 in dining room

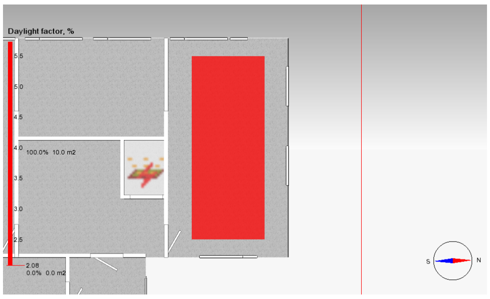


(a) Case7: $D_{TM} = 0.8$

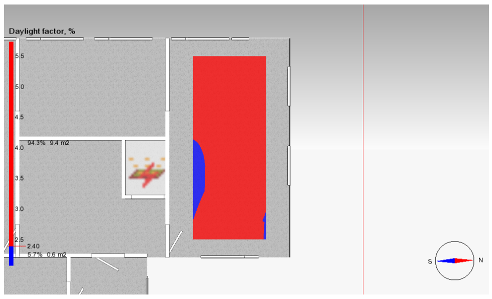


(b) Case7: $D_T = 2.4$

Figure 45: Daylight distribution in plan view for case 7 in dining room

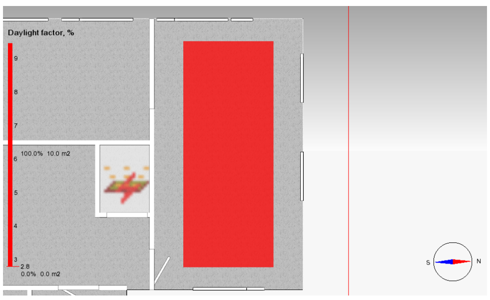


(a) Case8: $D_{TM} = 0.8$

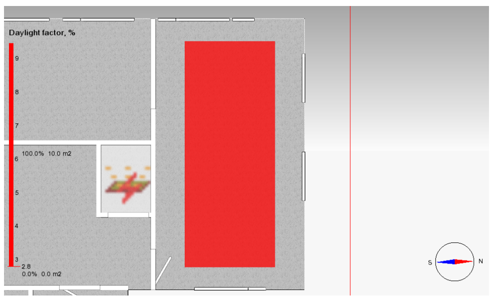


(b) Case8: $D_T = 2.4$

Figure 46: Daylight distribution in plan view for case 8 in dining room

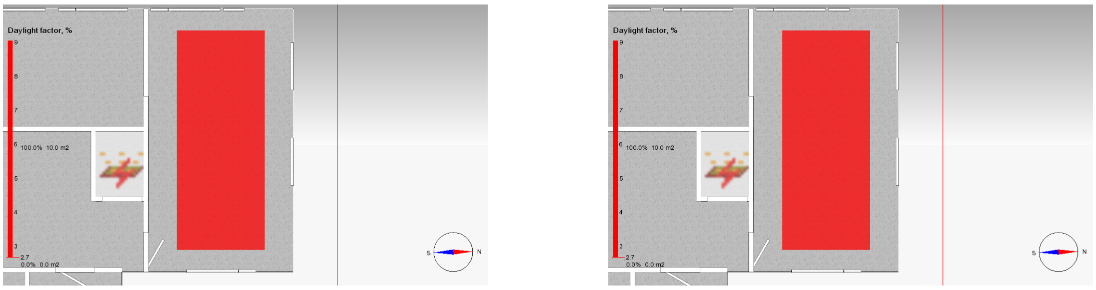


(a) Case9: $D_{TM} = 0.8$



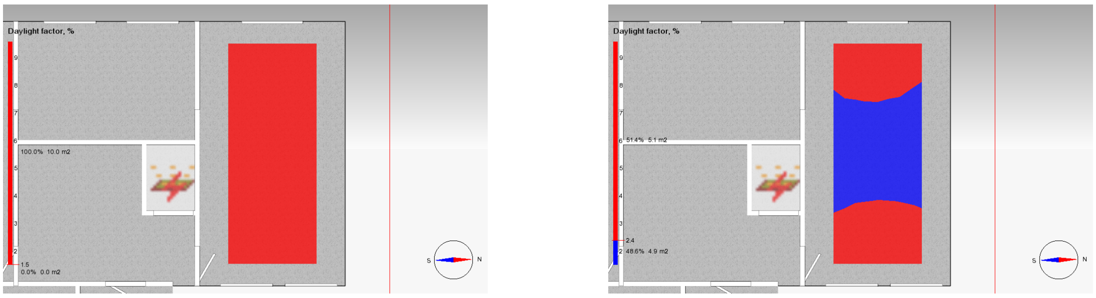
(b) Case9: $D_T = 2.4$

Figure 47: Daylight distribution in plan view for case 9 in dining room



(a) Case10: D$_{TM}$ $= 0.8$ (b) Case10: D$_{T}$ $= 2.4$

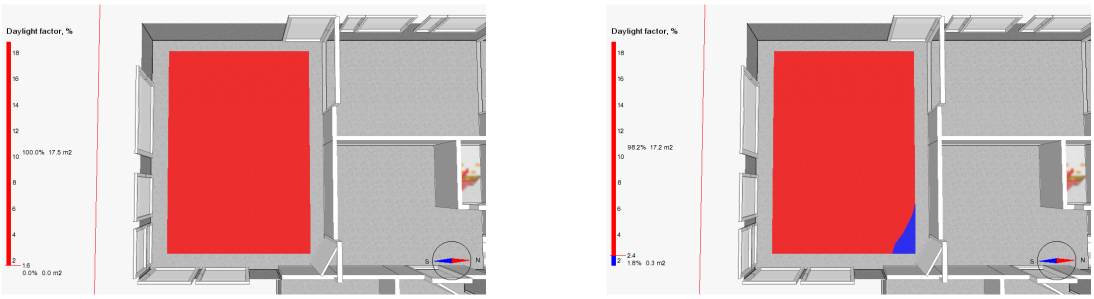
Figure 48: Daylight distribution in plan view for case 10 in dining room



(a) Case optimal: D$_{TM}$ $= 0.8$ (b) Case optimal: D$_{T}$ $= 2.4$

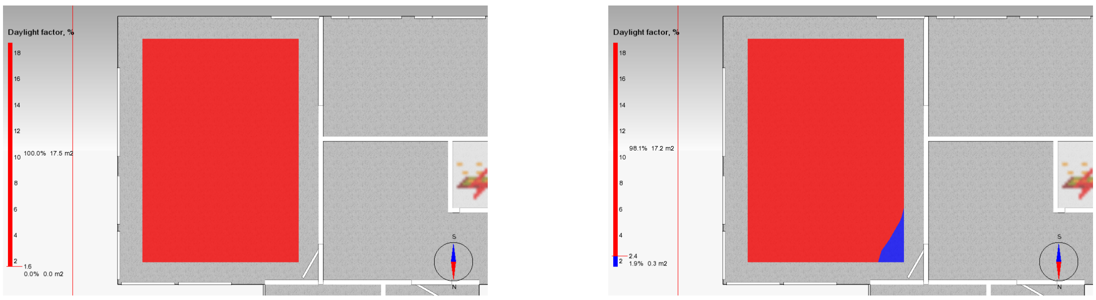
Figure 49: Daylight distribution in plan view for case optimal in dining room

B.3 Living room ground floor



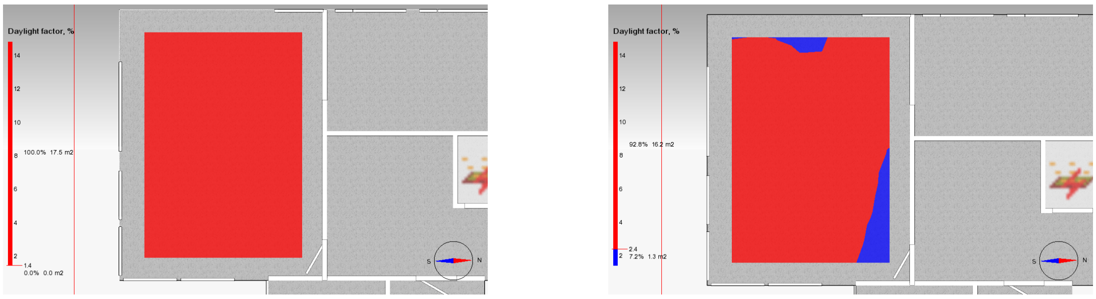
(a) Case0: D$_{TM}$ $= 0.8$ (b) Case0: D$_{T}$ $= 2.4$

Figure 50: Daylight distribution in plan view for case 0 in living room ground floor



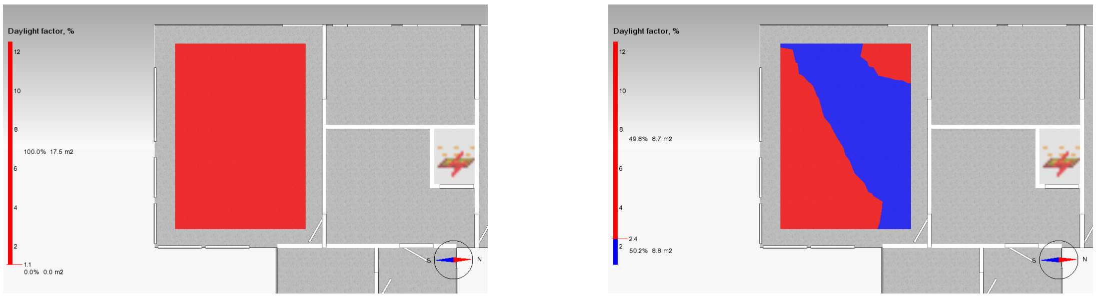
(a) Case1: D$_{TM}$ $= 0.8$ (b) Case1: D$_{T}$ $= 2.4$

Figure 51: Daylight distribution in plan view for case 1 in living room ground floor



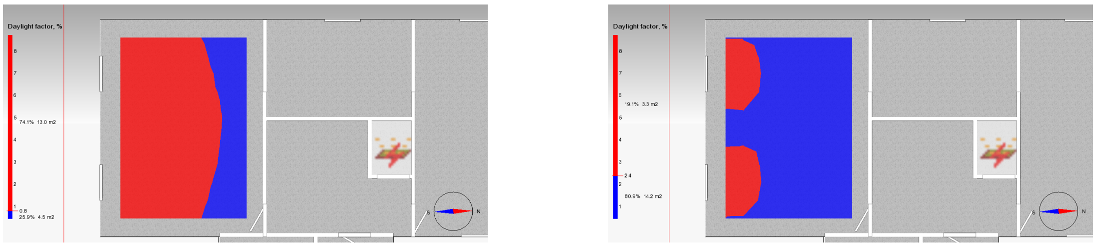
(a) Case2: $D_{TM} = 0.8$ (b) Case2: $D_T = 2.4$

Figure 52: Daylight distribution in plan view for case 2 in living room ground floor



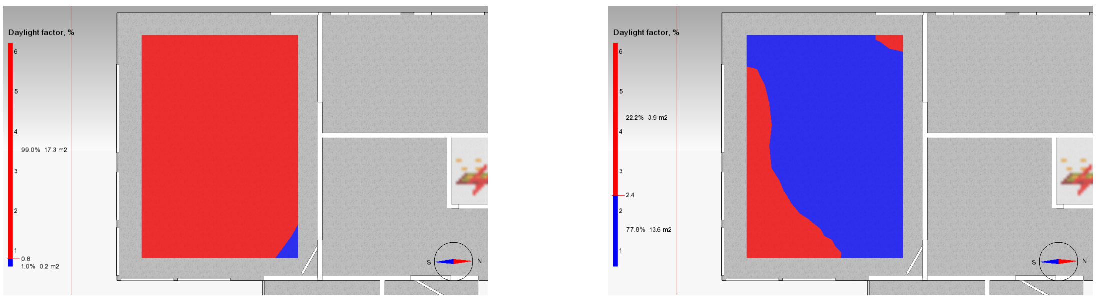
(a) Case3: $D_{TM} = 0.8$ (b) Case3: $D_T = 2.4$

Figure 53: Daylight distribution in plan view for case 3 in living room ground floor



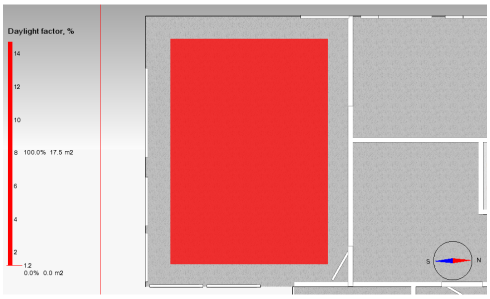
(a) Case4: $D_{TM} = 0.8$ (b) Case4: $D_T = 2.4$

Figure 54: Daylight distribution in plan view for case 4 in living room ground floor

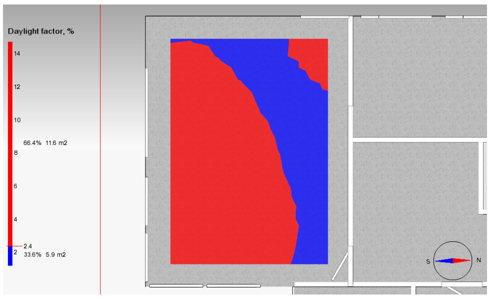


(a) Case5: $D_{TM} = 0.8$ (b) Case5: $D_T = 2.4$

Figure 55: Daylight distribution in plan view for case 5 in living room ground floor

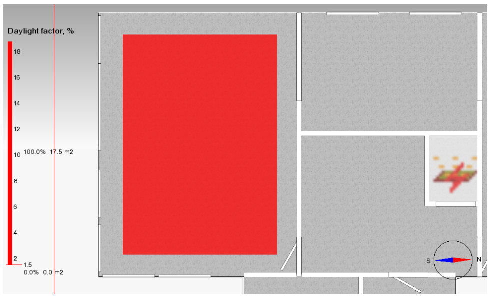


(a) Case6: $D_{TM} = 0.8$

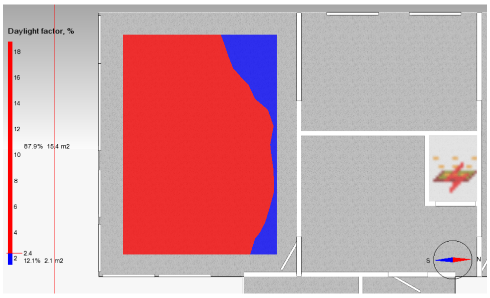


(b) Case6: $D_T = 2.4$

Figure 56: Daylight distribution in plan view for case 6 in living room ground floor

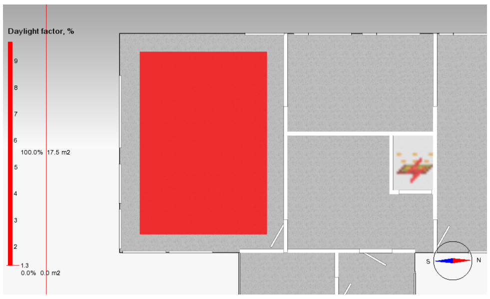


(a) Case7: $D_{TM} = 0.8$

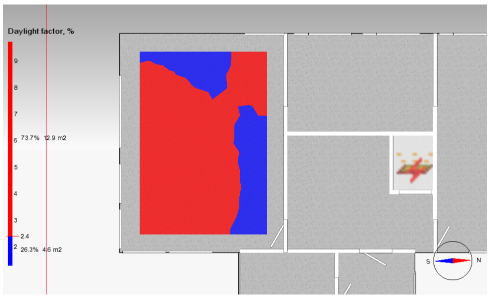


(b) Case7: $D_T = 2.4$

Figure 57: Daylight distribution in plan view for case 7 in living room ground floor

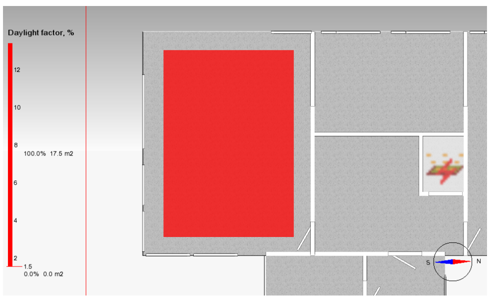


(a) Case8: $D_{TM} = 0.8$

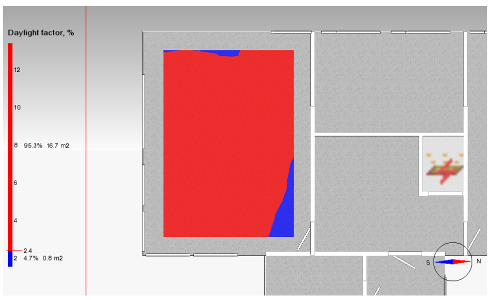


(b) Case8: $D_T = 2.4$

Figure 58: Daylight distribution in plan view for case 8 in living room ground floor

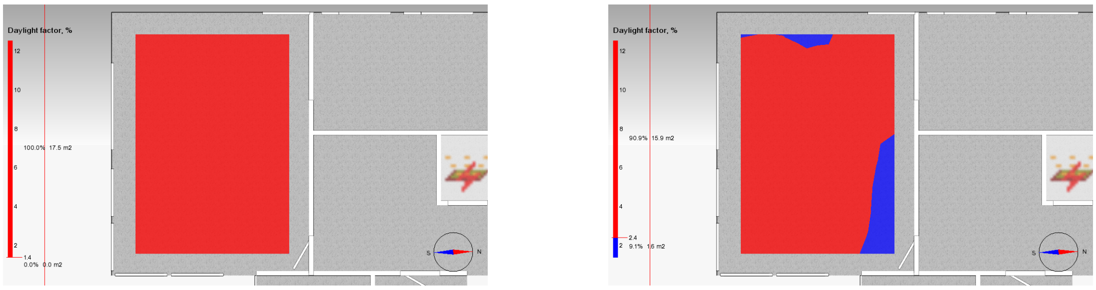


(a) Case9: $D_{TM} = 0.8$



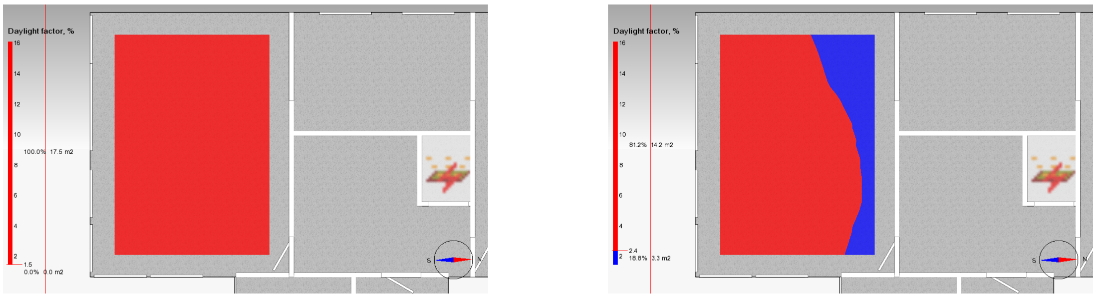
(b) Case9: $D_T = 2.4$

Figure 59: Daylight distribution in plan view for case 9 in living room ground floor



(a) Case10: D$_{TM}$ $= 0.8$ **(b)** Case10: D$_{T}$ $= 2.4$

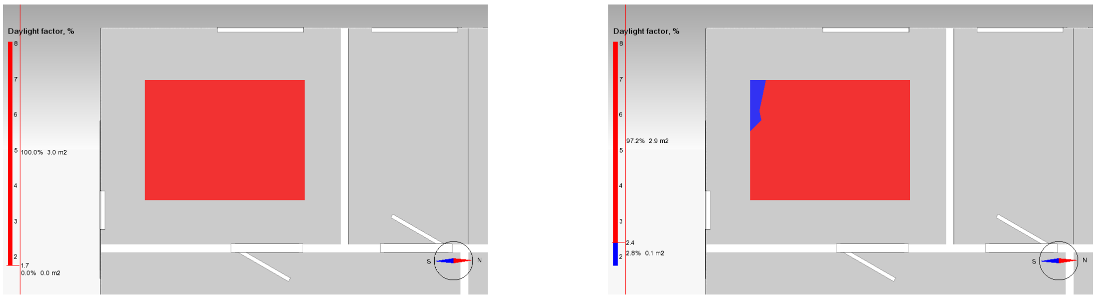
Figure 60: Daylight distribution in plan view for case 10 in living room ground floor



(a) Case optimal: D$_{TM}$ $= 0.8$ **(b)** Case optimal: D$_{T}$ $= 2.4$

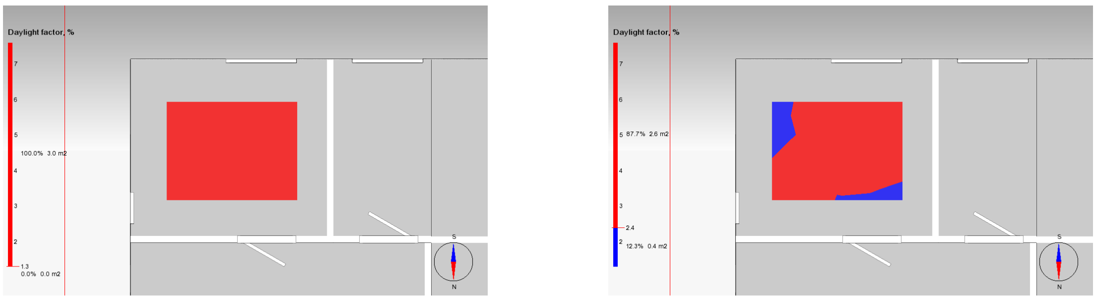
Figure 61: Daylight distribution in plan view for case optimal in living room ground floor

B.4 Bedroom 1



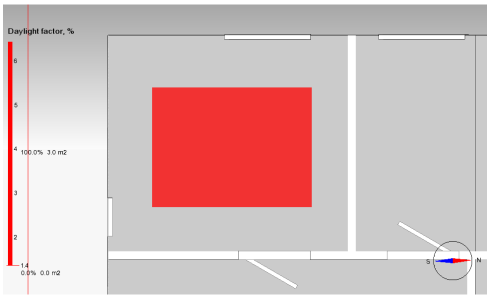
(a) Case0: D$_{TM}$ $= 0.8$ **(b)** Case0: D$_{T}$ $= 2.4$

Figure 62: Daylight distribution in plan view for case 0 in bedroom 1

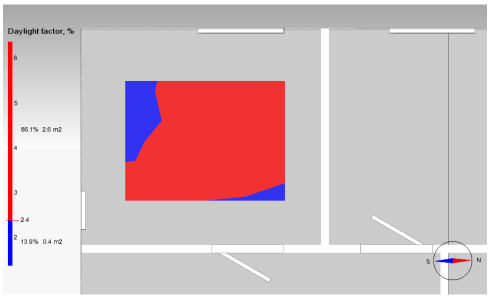


(a) Case1: D$_{TM}$ $= 0.8$ **(b)** Case1: D$_{T}$ $= 2.4$

Figure 63: Daylight distribution in plan view for case 1 in bedroom 1

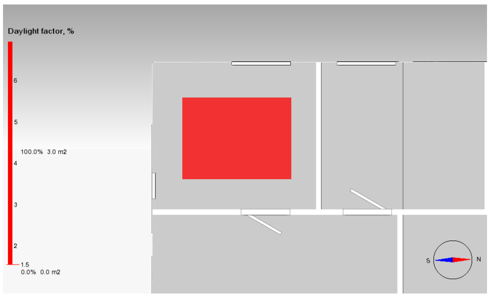


(a) Case2: $D_{TM} = 0.8$

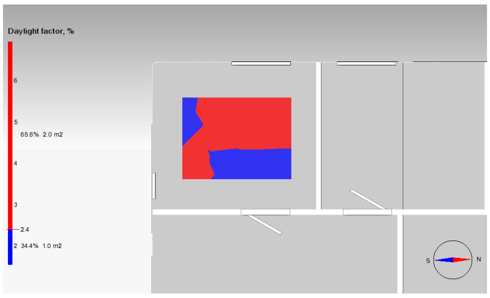


(b) Case2: $D_{T} = 2.4$

Figure 64: Daylight distribution in plan view for case 2 in bedroom 1

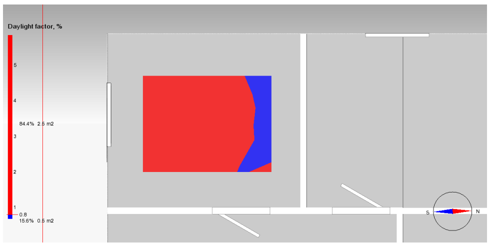


(a) Case3: $D_{TM} = 0.8$

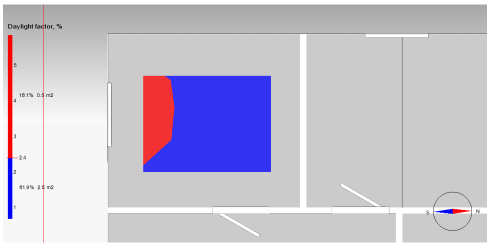


(b) Case3: $D_{T} = 2.4$

Figure 65: Daylight distribution in plan view for case 3 in bedroom 1

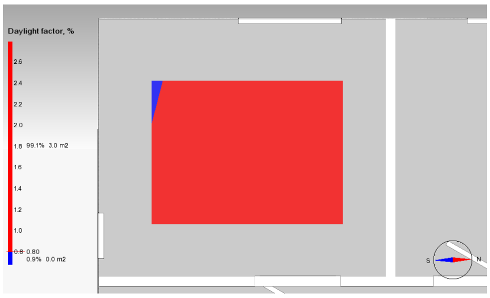


(a) Case4: $D_{TM} = 0.8$

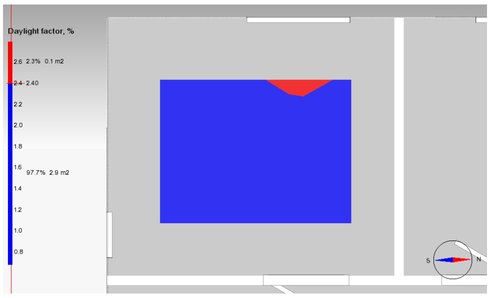


(b) Case4: $D_{T} = 2.4$

Figure 66: Daylight distribution in plan view for case 4 in bedroom 1

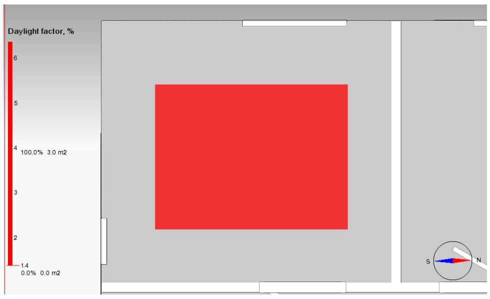


(a) Case5: $D_{TM} = 0.8$

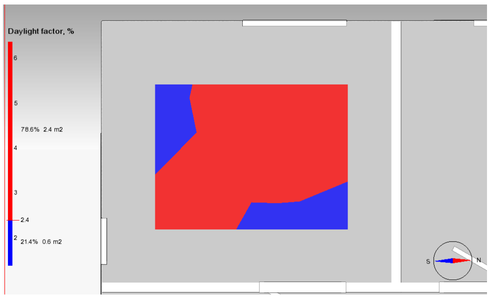


(b) Case5: $D_{T} = 2.4$

Figure 67: Daylight distribution in plan view for case 5 in bedroom 1

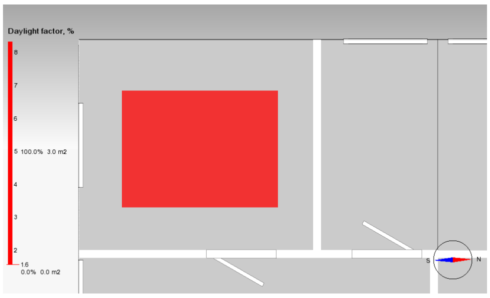


(a) Case6: $D_{TM} = 0.8$

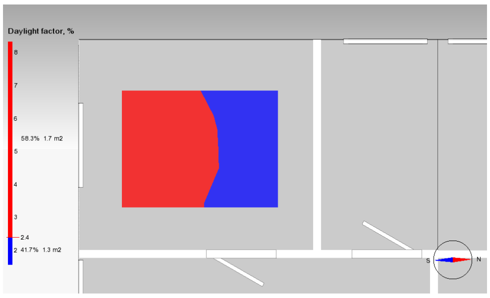


(b) Case6: $D_T = 2.4$

Figure 68: Daylight distribution in plan view for case 6 in bedroom 1

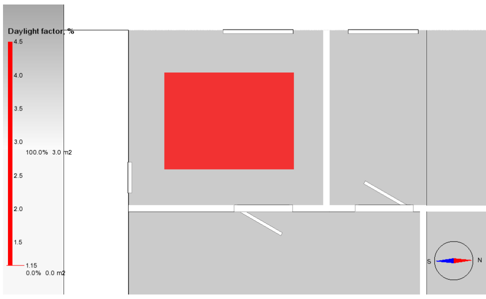


(a) Case7: $D_{TM} = 0.8$

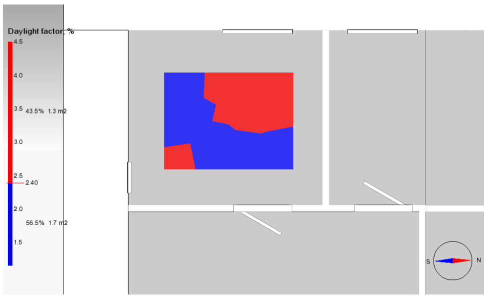


(b) Case7: $D_T = 2.4$

Figure 69: Daylight distribution in plan view for case 7 in bedroom 1

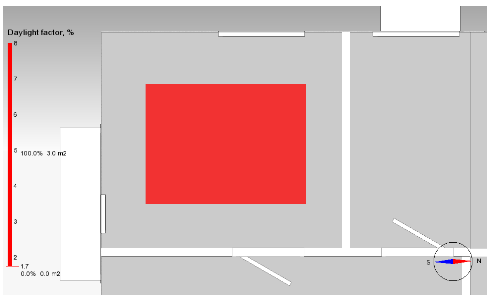


(a) Case8: $D_{TM} = 0.8$

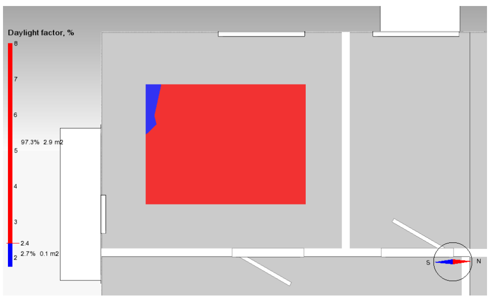


(b) Case8: $D_T = 2.4$

Figure 70: Daylight distribution in plan view for case 8 in bedroom 1

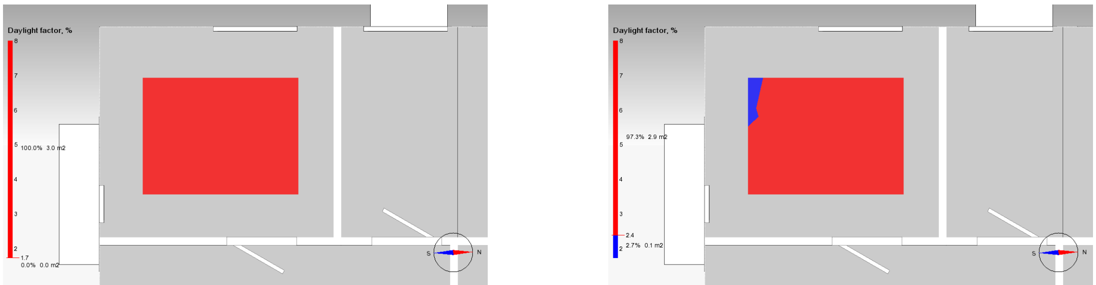


(a) Case9: $D_{TM} = 0.8$



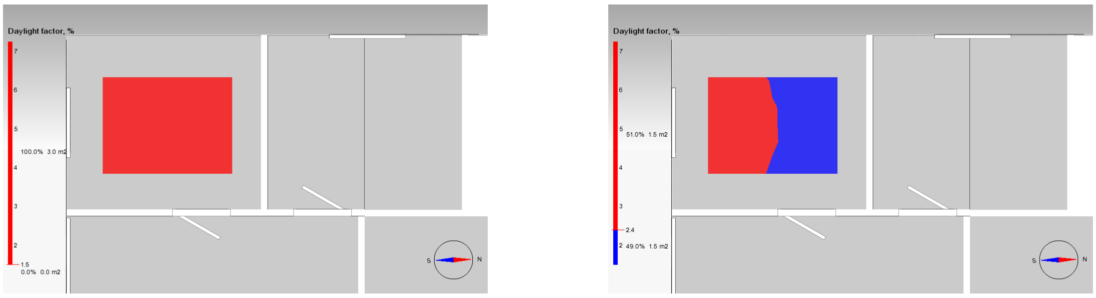
(b) Case9: $D_T = 2.4$

Figure 71: Daylight distribution in plan view for case 9 in bedroom 1



(a) Case10: $D_{TM} = 0.8$ **(b)** Case10: $D_T = 2.4$

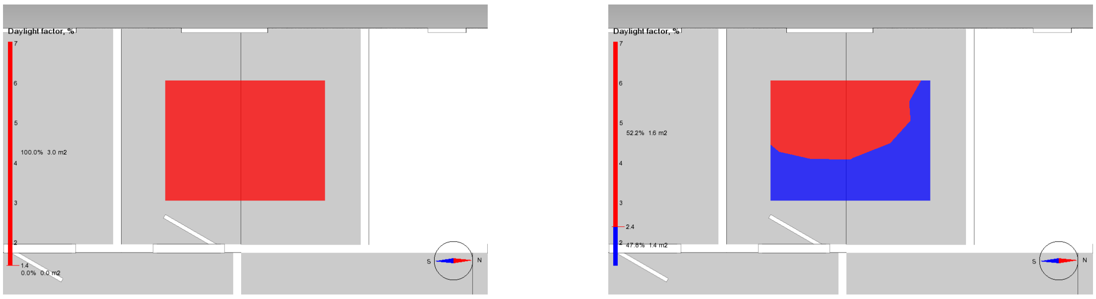
Figure 72: Daylight distribution in plan view for case 10 in bedroom 1



(a) Case optimal: $D_{TM} = 0.8$ **(b)** Case optimal: $D_T = 2.4$

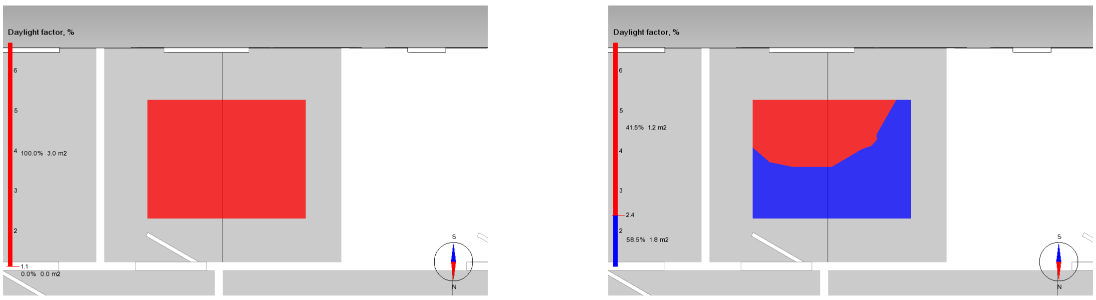
Figure 73: Daylight distribution in plan view for case optimal in bedroom 1

B.5 Bedroom 2



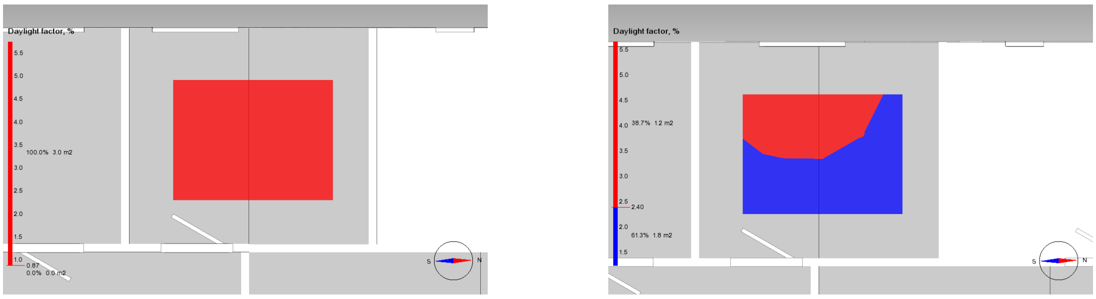
(a) Case0: $D_{TM} = 0.8$ **(b)** Case0: $D_T = 2.4$

Figure 74: Daylight distribution in plan view for case 0 in bedroom 2



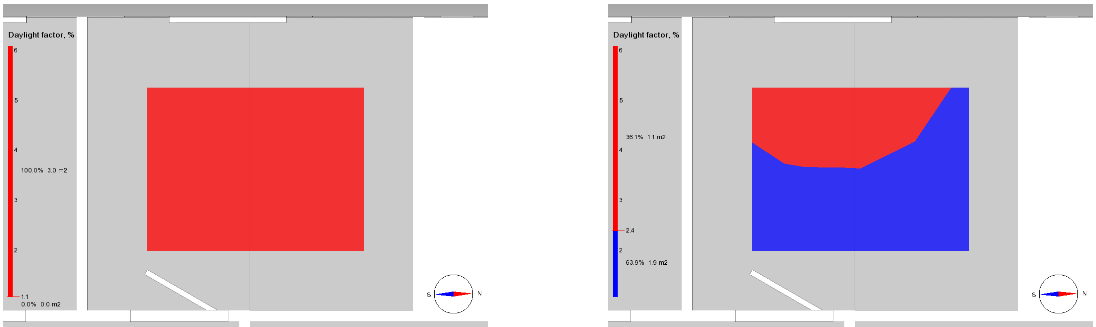
(a) Case1: $D_{TM} = 0.8$ **(b)** Case1: $D_T = 2.4$

Figure 75: Daylight distribution in plan view for case 1 in bedroom 2



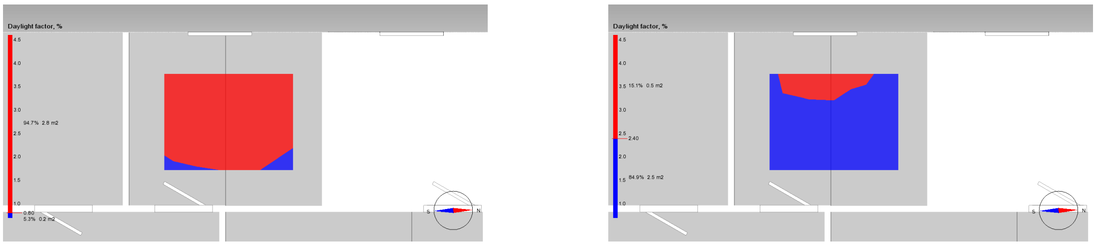
(a) Case2: $D_{TM} = 0.8$ **(b)** Case2: $D_T = 2.4$

Figure 76: Daylight distribution in plan view for case 2 in bedroom 2



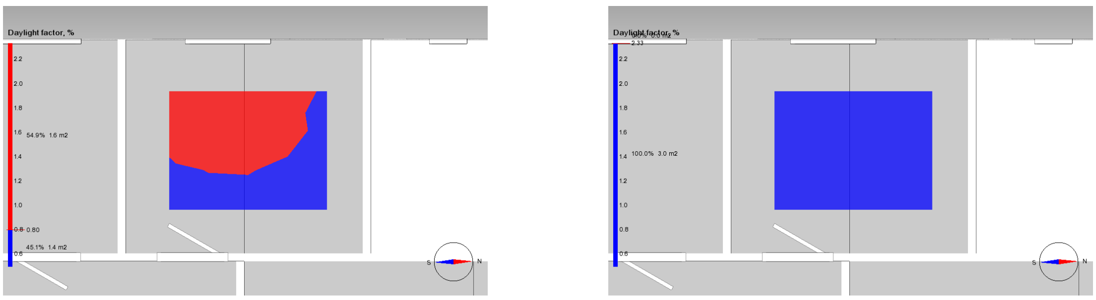
(a) Case3: $D_{TM} = 0.8$ **(b)** Case3: $D_T = 2.4$

Figure 77: Daylight distribution in plan view for case 3 in bedroom 2



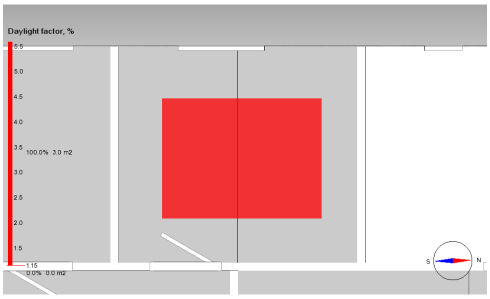
(a) Case4: $D_{TM} = 0.8$ **(b)** Case4: $D_T = 2.4$

Figure 78: Daylight distribution in plan view for case 4 in bedroom 2

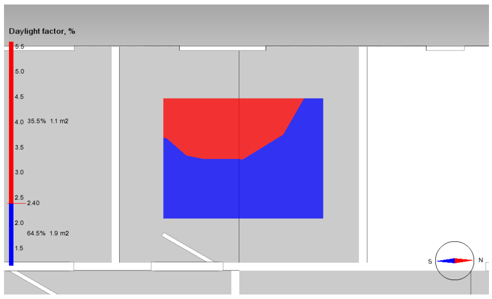


(a) Case5: $D_{TM} = 0.8$ **(b)** Case5: $D_T = 2.4$

Figure 79: Daylight distribution in plan view for case 5 in bedroom 2

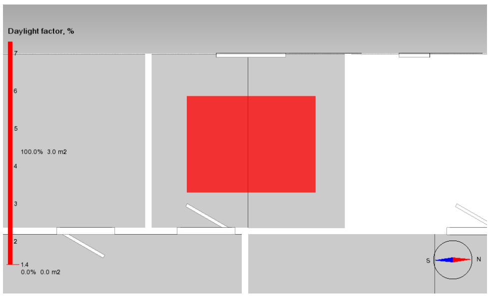


(a) Case6: $D_{TM} = 0.8$

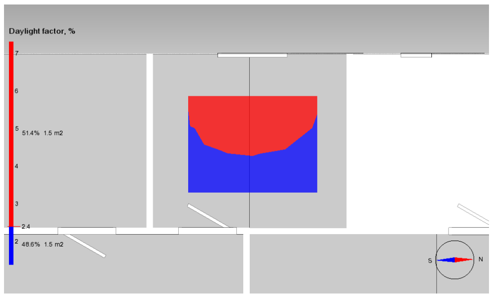


(b) Case6: $D_T = 2.4$

Figure 80: Daylight distribution in plan view for case 6 in bedroom 2

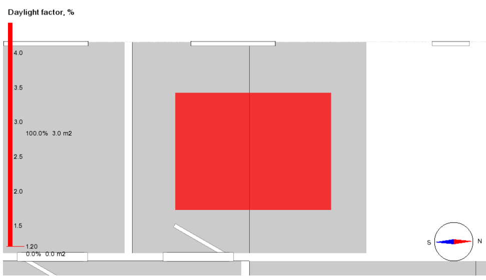


(a) Case7: $D_{TM} = 0.8$

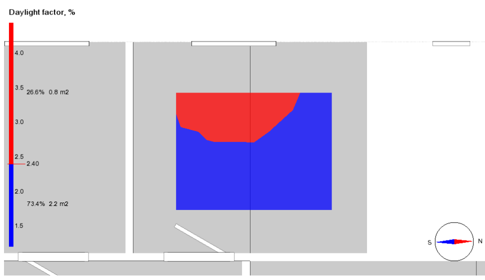


(b) Case7: $D_T = 2.4$

Figure 81: Daylight distribution in plan view for case 7 in bedroom 2

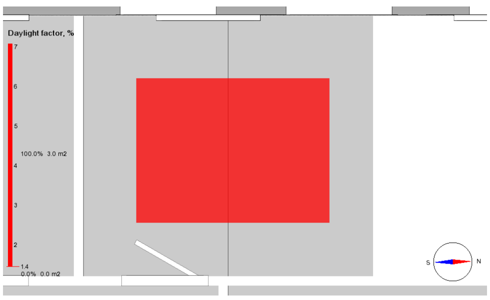


(a) Case8: $D_{TM} = 0.8$

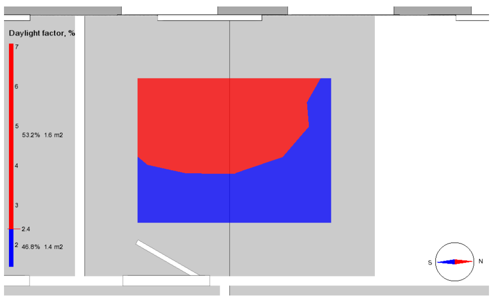


(b) Case8: $D_T = 2.4$

Figure 82: Daylight distribution in plan view for case 8 in bedroom 2

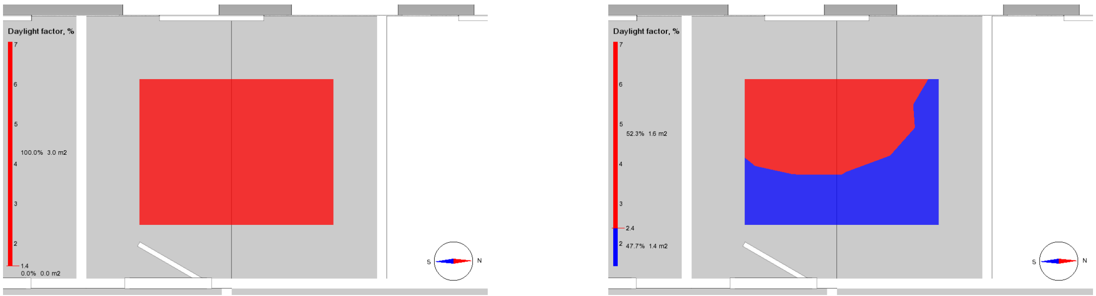


(a) Case9: $D_{TM} = 0.8$



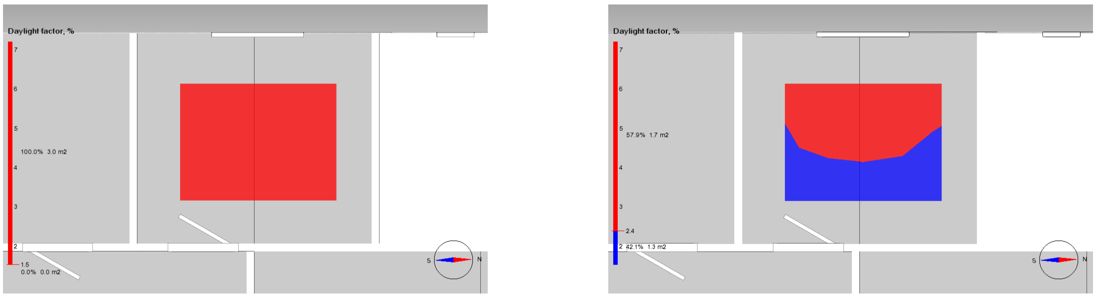
(b) Case9: $D_T = 2.4$

Figure 83: Daylight distribution in plan view for case 9 in bedroom 2



(a) Case10: $D_{TM} = 0.8$ **(b)** Case10: $D_T = 2.4$

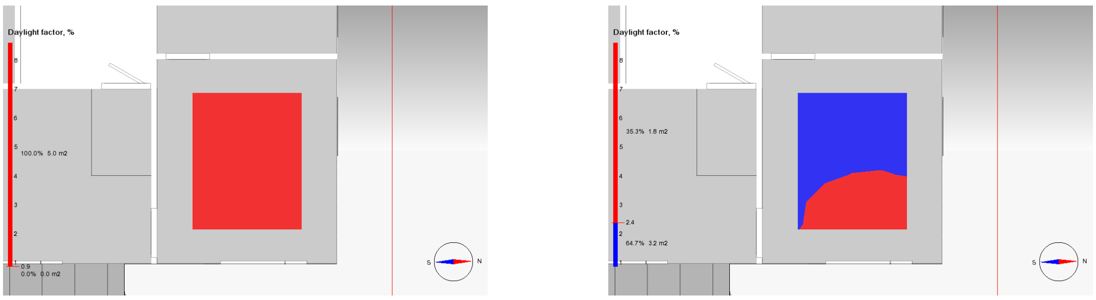
Figure 84: Daylight distribution in plan view for case 10 in bedroom 2



(a) Case optimal: $D_{TM} = 0.8$ **(b)** Case optimal: $D_T = 2.4$

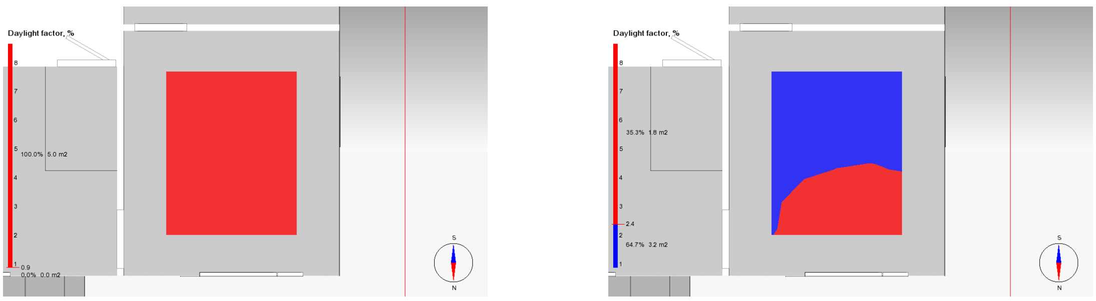
Figure 85: Daylight distribution in plan view for case optimal in bedroom 2

B.6 Bedroom 3



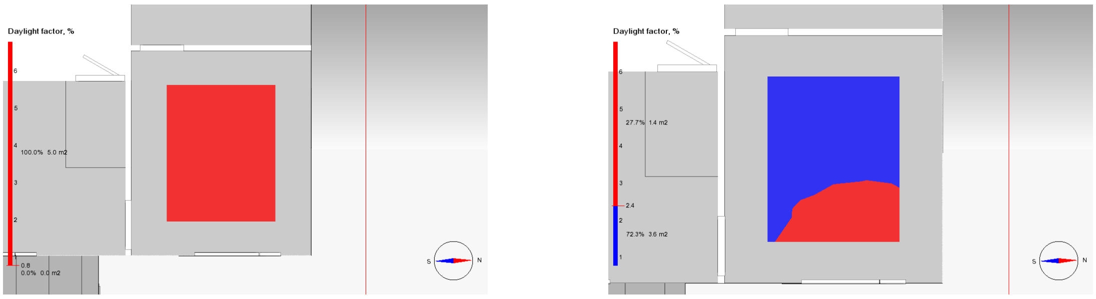
(a) Case0: $D_{TM} = 0.8$ **(b)** Case0: $D_T = 2.4$

Figure 86: Daylight distribution in plan view for case 0 in bedroom 3



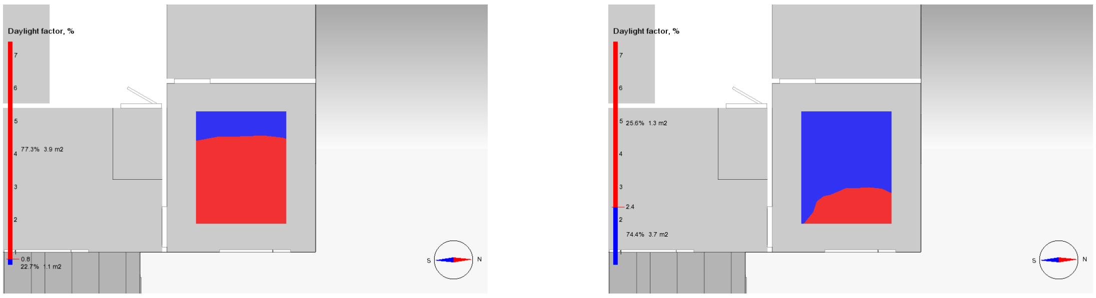
(a) Case1: $D_{TM} = 0.8$ **(b)** Case1: $D_T = 2.4$

Figure 87: Daylight distribution in plan view for case 1 in bedroom 3



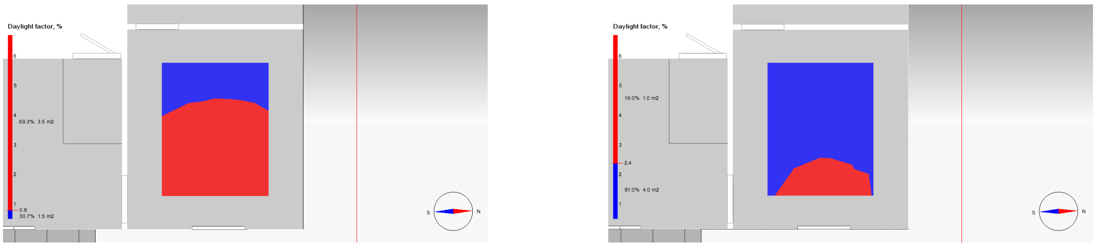
(a) Case2: $D_{TM} = 0.8$ (b) Case2: $D_T = 2.4$

Figure 88: Daylight distribution in plan view for case 2 in bedroom 3



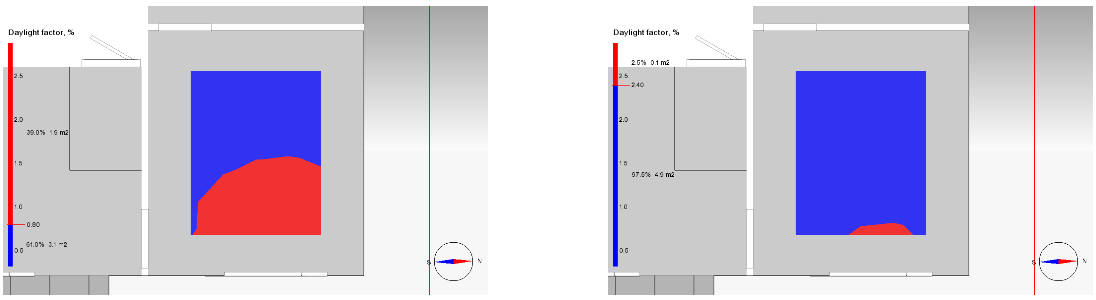
(a) Case3: $D_{TM} = 0.8$ (b) Case3: $D_T = 2.4$

Figure 89: Daylight distribution in plan view for case 3 in bedroom 3



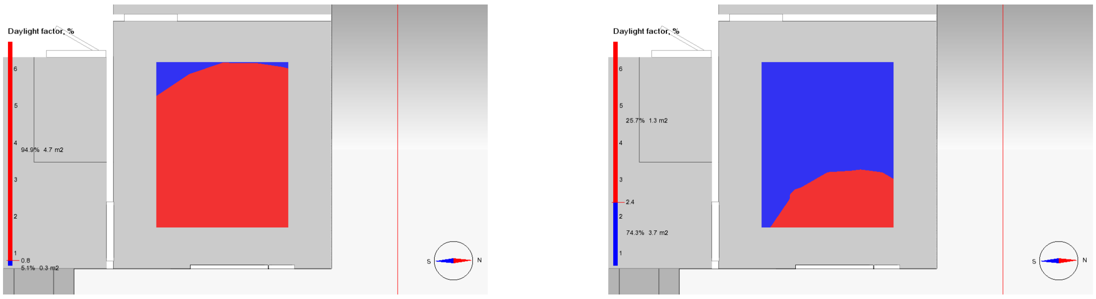
(a) Case4: $D_{TM} = 0.8$ (b) Case4: $D_T = 2.4$

Figure 90: Daylight distribution in plan view for case 4 in bedroom 3



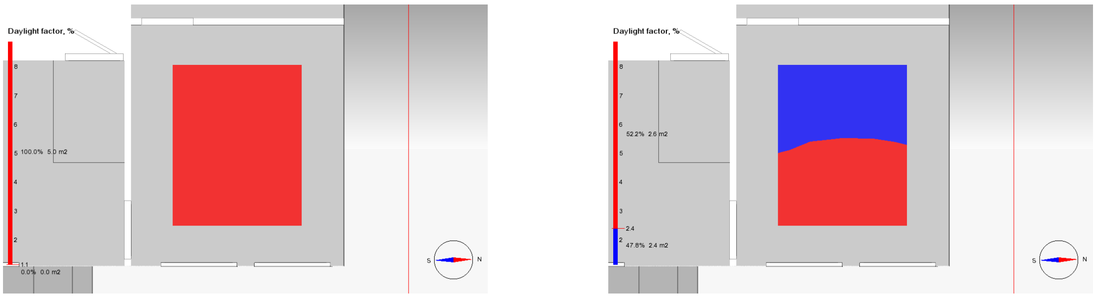
(a) Case5: $D_{TM} = 0.8$ (b) Case5: $D_T = 2.4$

Figure 91: Daylight distribution in plan view for case 5 in bedroom 3



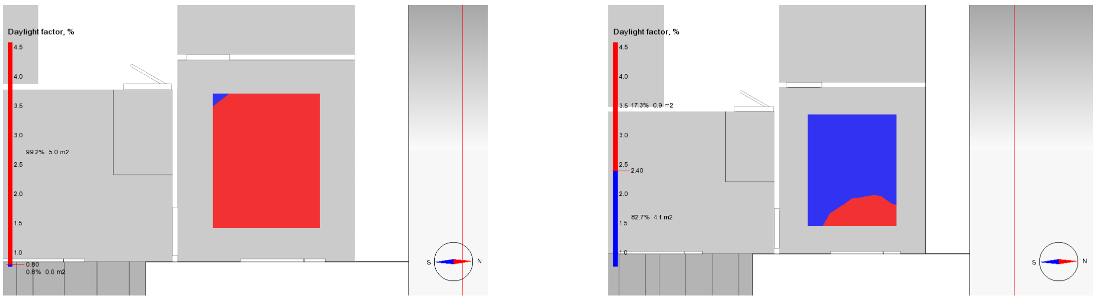
(a) Case6: $D_{TM} = 0.8$ (b) Case6: $D_T = 2.4$

Figure 92: Daylight distribution in plan view for case 6 in bedroom 3



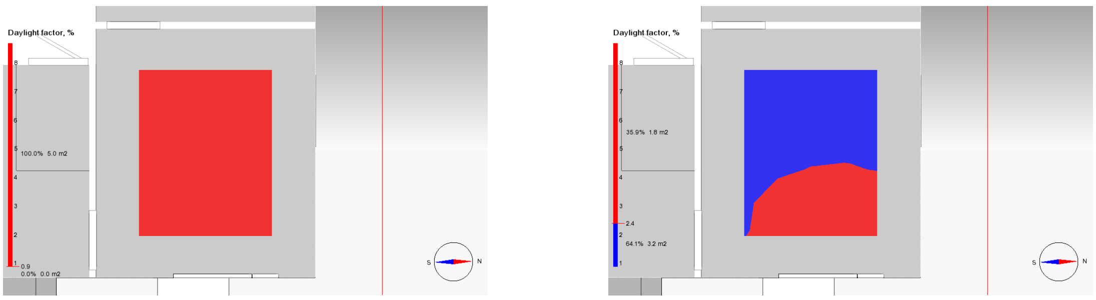
(a) Case7: $D_{TM} = 0.8$ (b) Case7: $D_T = 2.4$

Figure 93: Daylight distribution in plan view for case 7 in bedroom 3



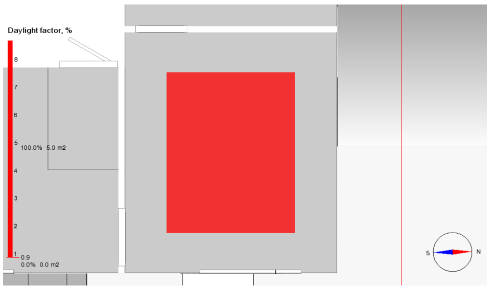
(a) Case8: $D_{TM} = 0.8$ (b) Case8: $D_T = 2.4$

Figure 94: Daylight distribution in plan view for case 8 in bedroom 3

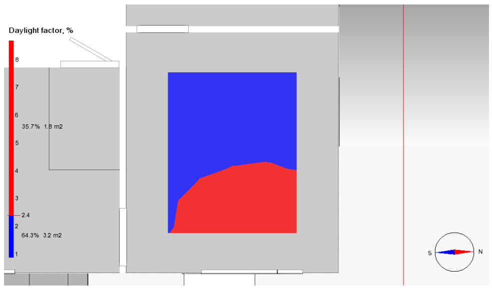


(a) Case9: $D_{TM} = 0.8$ (b) Case9: $D_T = 2.4$

Figure 95: Daylight distribution in plan view for case 9 in bedroom 3

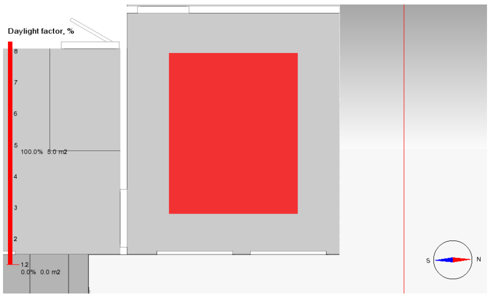


(a) Case10: $D_{TM} = 0.8$

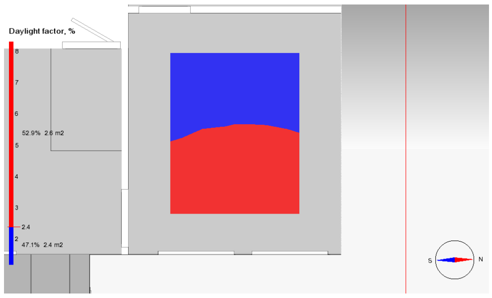


(b) Case10: $D_T = 2.4$

Figure 96: Daylight distribution in plan view for case 10 in bedroom 3



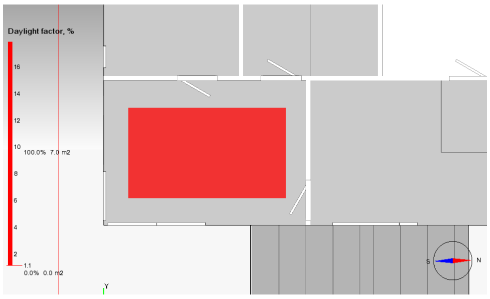
(a) Case optimal: $D_{TM} = 0.8$



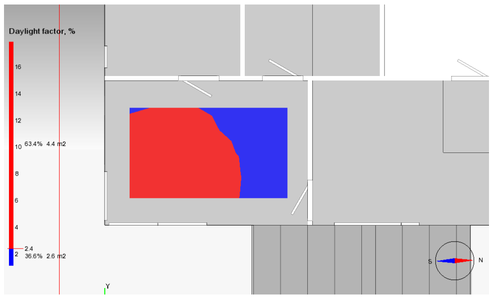
(b) Case optimal: $D_T = 2.4$

Figure 97: Daylight distribution in plan view for case optimal in bedroom 3

B.7 Living room first floor

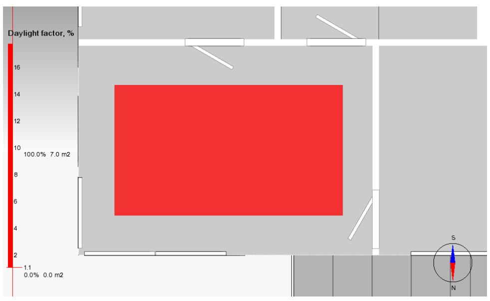


(a) Case0: $D_{TM} = 0.8$

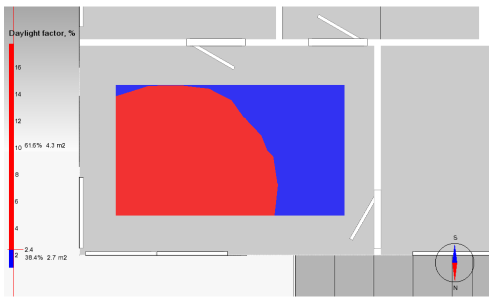


(b) Case0: $D_T = 2.4$

Figure 98: Daylight distribution in plan view for case 0 in living room first floor

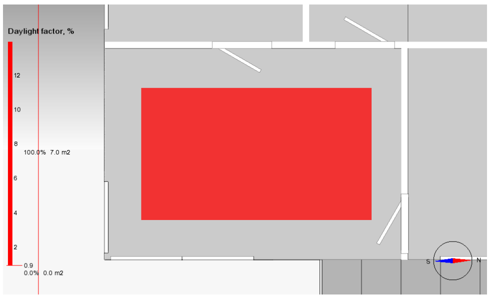


(a) Case1: $D_{TM} = 0.8$

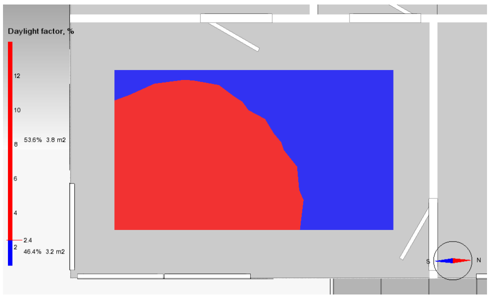


(b) Case1: $D_T = 2.4$

Figure 99: Daylight distribution in plan view for case 1 in living room first floor

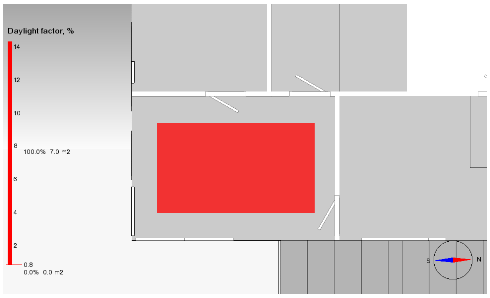


(a) Case2: $D_{TM} = 0.8$

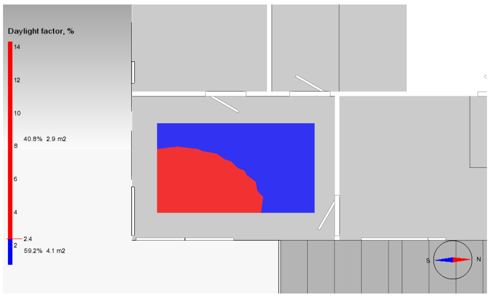


(b) Case2: $D_{T} = 2.4$

Figure 100: Daylight distribution in plan view for case 2 in living room first floor

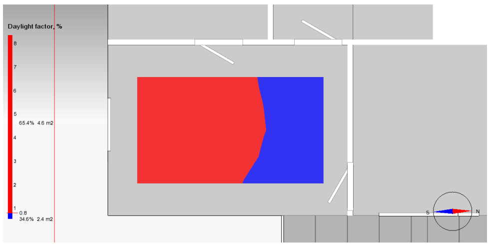


(a) Case3: $D_{TM} = 0.8$

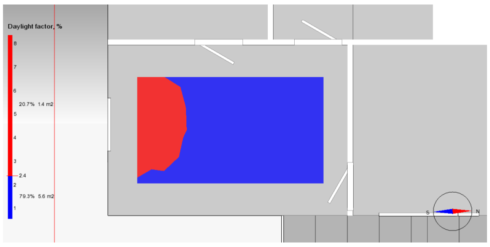


(b) Case3: $D_{T} = 2.4$

Figure 101: Daylight distribution in plan view for case 3 in living room first floor

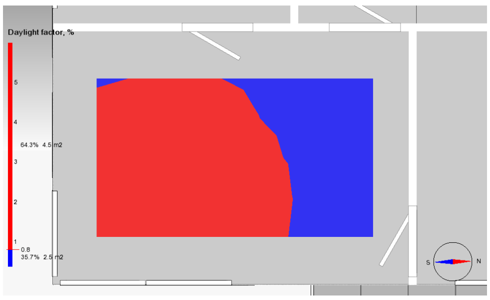


(a) Case4: $D_{TM} = 0.8$

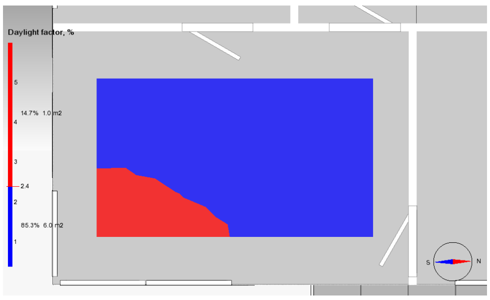


(b) Case4: $D_{T} = 2.4$

Figure 102: Daylight distribution in plan view for case 4 in living room first floor

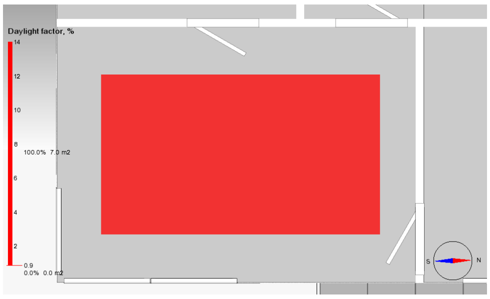


(a) Case5: $D_{TM} = 0.8$

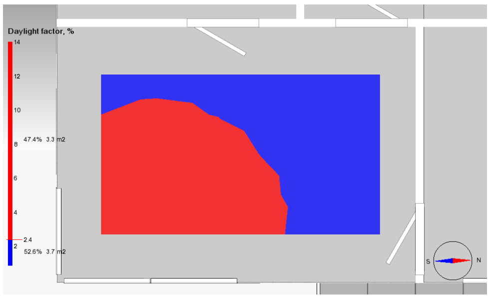


(b) Case5: $D_{T} = 2.4$

Figure 103: Daylight distribution in plan view for case 5 in living room first floor

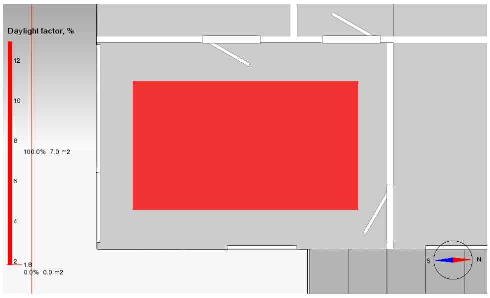


(a) Case6: $D_{TM} = 0.8$

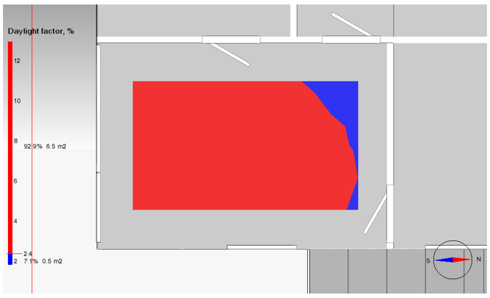


(b) Case6: $D_T = 2.4$

Figure 104: Daylight distribution in plan view for case 6 in living room first floor

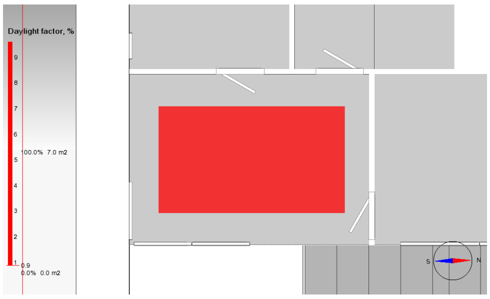


(a) Case7: $D_{TM} = 0.8$

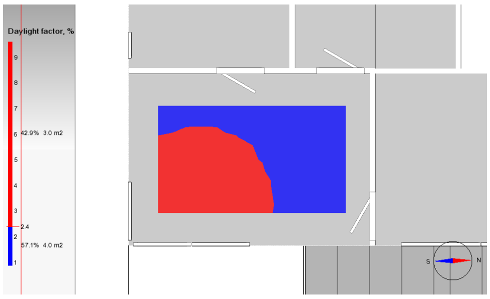


(b) Case7: $D_T = 2.4$

Figure 105: Daylight distribution in plan view for case 7 in living room first floor

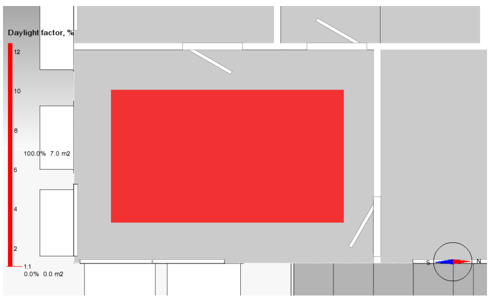


(a) Case8: $D_{TM} = 0.8$

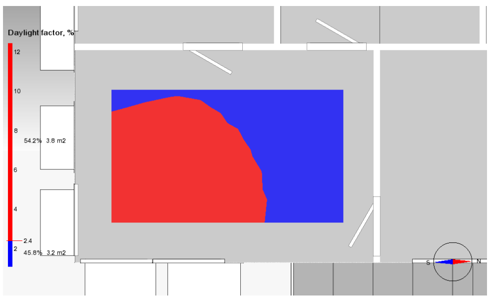


(b) Case8: $D_T = 2.4$

Figure 106: Daylight distribution in plan view for case 8 in living room first floor

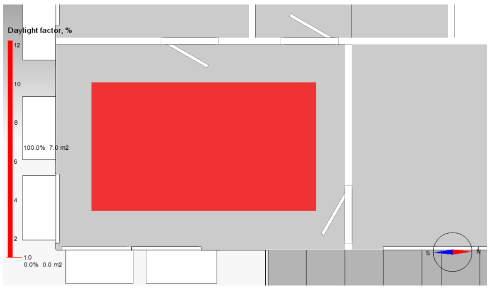


(a) Case9: $D_{TM} = 0.8$

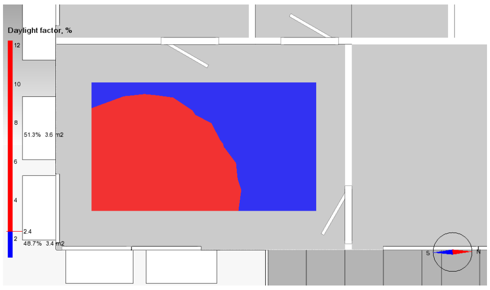


(b) Case9: $D_T = 2.4$

Figure 107: Daylight distribution in plan view for case 9 in living room first floor

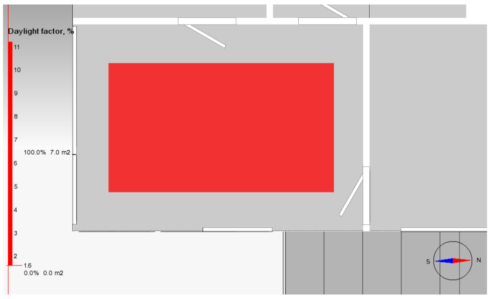


(a) Case10: $D_{TM} = 0.8$

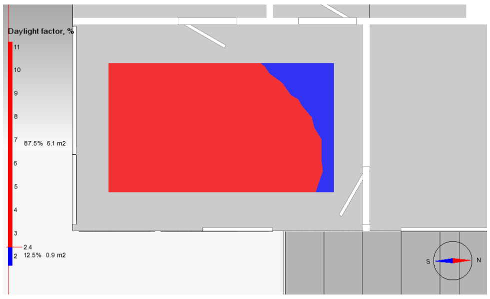


(b) Case10: $D_T = 2.4$

Figure 108: Daylight distribution in plan view for case 10 in living room first floor



(a) Case optimal: $D_{TM} = 0.8$



(b) Case optimal: $D_T = 2.4$

Figure 109: Daylight distribution in plan view for case optimal in living room first floor

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