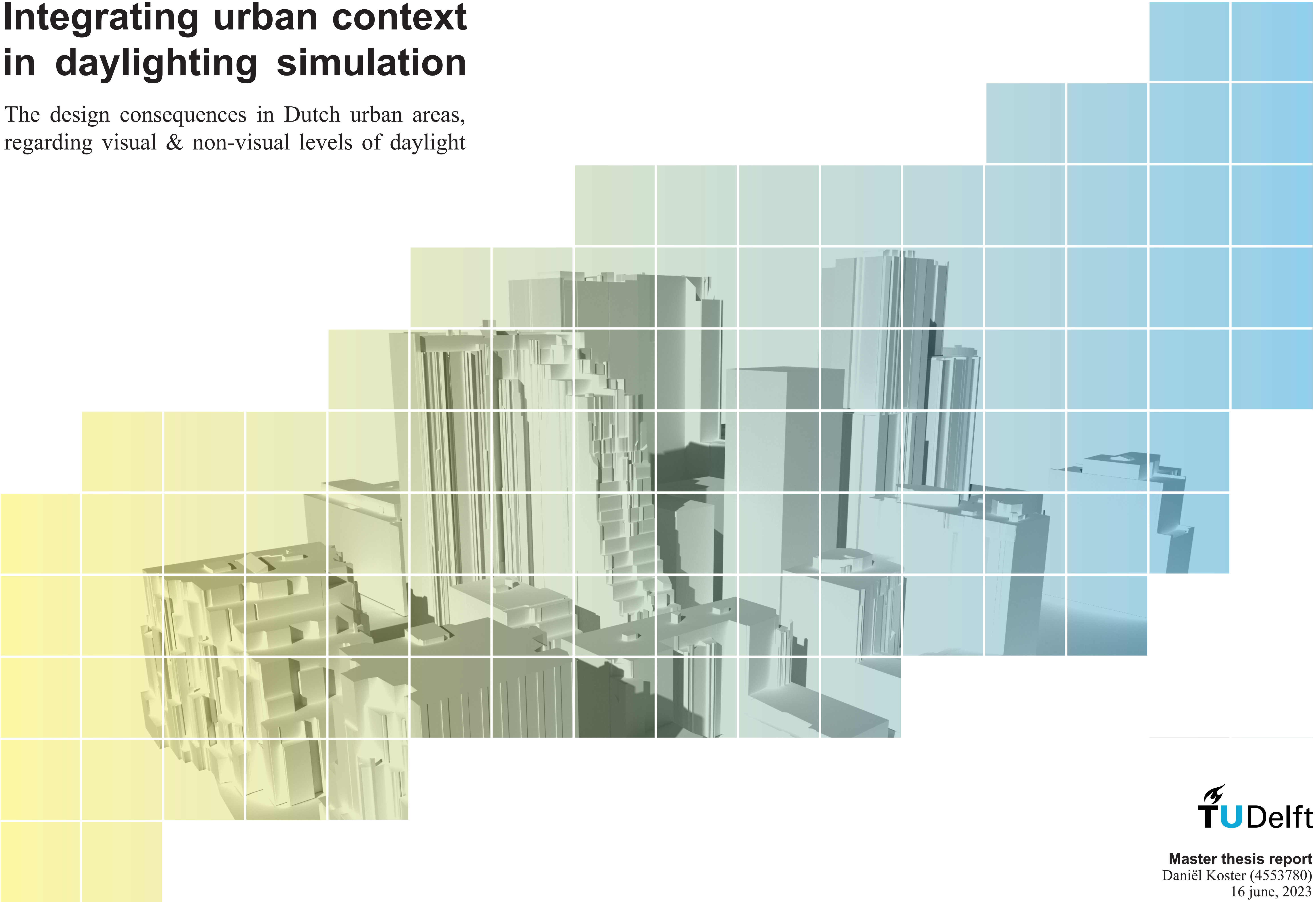
Integrating urban context in daylighting simulation

The design consequences in Dutch urban areas, regarding visual & non-visual levels of daylight



TU Delft

Master thesis report

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16 june, 2023

Abstract

The Netherlands is facing a housing demand of 1 million homes before 2030. Most of these residences are planned to be built in and around existing cities, causing an increase in urban densities with sub-optimal indoor daylighting conditions as a result. Simultaneously, the daylight assessment methodology for buildings in the Netherlands is set to change from the Dutch NEN 2057 to the European EN 17037. The European norm uses more accurate metrics to express daylighting performance but does not consider urban context (i.e. external buildings) in the simulation models. As a result, a concern is that indoor daylighting in dense urban areas is inadequately protected. Moreover, it is unknown to what extent the urban context affects the well-being of humans, regarding visual and non-visual levels of daylight.

A multitude of daylight simulations is run and analysed in the thesis to better understand the impact of the urban context on indoor daylighting performance. Visual daylighting is assessed following the EN 17037 methodology with urban context integrated. Non-visual daylight performance is assessed using two novel metrics: melanopic autonomy and melanopic isotropy. The results have revealed that the discrepancy between simulations with and without the integration of urban context is up to 90% for realistic residences throughout the Netherlands, depending on urban characteristics and density. On average, indoor daylighting is decreased by 36% when the urban context is integrated with the EN 17037. The non-visual stimulus was found to be sufficient in residences that are compliant with EU_{min} levels but insufficient for residences that only comply with the Dutch building code. Sky view factor (SVF) and Building Floor were found to be useful indicators of daylighting performance in early design stages. Urban density indicators such as the FSI and OSR seem to be negatively correlated with daylighting performance.

The thesis concludes with the advice to include urban context in daylighting simulations so that bad daylighting can be properly mitigated. Effective mitigation strategies are increasing glass transmission values, interior reflectance values, and exterior building reflectance values. Another effective strategy is to avoid bad daylighting conditions in the first place by not positioning residences on the first 5 building floors in high-density urban areas. The results from this thesis can be used by daylighting designers and architects who are interested in ensuring adequate and healthy daylighting conditions in the residences they design: not only in digital environments but in the real world.

Keywords: daylight, simulation, non-visual daylight, urban context, EN 17037, urban density, sky view factor

TU Delft

Delft University of Technology
MSc track - Building Technology
Climate design graduation studio
Architectural engineering + technology (AE+T)

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Nomenclature

AO		angle of obstruction
BBL		besluit bouwwerken leefomgeving (decree for the built environment)
CAI	W/m2	cumulative annual irradiance
CBDM		climate-based daylight modelling
DA	%	daylight autonomy
sDA	%	spatial daylight autonomy
DF	-	daylight factor
EML	lx	equivalent melanopic lux
EN		European norm
FSI	-	floor-space index
GH		Grasshopper (software)
GSI	-	ground-space index
HB		Honeybee (software)
IEQ		indoor environmental quality
L	-	layers
LB		Ladybug (software)
MA	%	melanopic autonomy
M-EDI	lx	melanopic-equivalent daylight illuminance
MI	%	melanopic isotropy
NEN		Nederlandse norm (Dutch norm)
NPR		Nederlandse praktijk richtlijn (Dutch code of practice)
OSR	-	open-space ratio
P	%	probability
SVF	-	sky view factor
SC	-	sensitivity coefficient
SD		standard deviation
SHGC	-	solar heat gain coefficient
SPD		spectral power distribution
TAI	klxh	total annual illuminance
WWR	-	window to wall ratio

Disclaimer

- Daylighting requirements such as EU_{min}, EU_{med} and EU_{high} are referencing to different levels of requirement following from the EN 17037:2018 (2018).

- Simulations 'in accordance with the EN 17037' are divergent on reflectance values in the simulation model.

- Northern facing windows are included in any dynamic CBDM simulation even though this is not allowed according to the NPR 4057.

- Not all data entries are used for analysis in the thesis report but do exist in a central database file. For questions and additional information about this database and this thesis, contact the author through email: dkoster@hotmail.nl.

Table of content

introduction

New construction in the built environment

There is a large demand for housing in the Netherlands: the population is growing (CBS, 2022), life expectancy is ever increasing (CBS, 2021) and the average size of a household is increasing (CBS, 2022). This causes inability to move house and causes rental rates and mortgages to be at an all-time high, resulting in unaffordable housing and therefore it has a negative effect on society and our built environment (CBS, 2022). To tackle these problems, the ministry of Housing and Spatial order has been pointing in one direction: the Netherlands must build 1 million homes before 2030 to help solving the housing shortage (Ministry of Housing and Spatial order, 2022).

The 1 million homes before 2030 are planned to be built across the Netherlands, of which 50% will be built in the provinces of North and South Holland. To give a starting impulse to the challenge of building 1 million homes, ca. 140.000 houses will be financed with the help of the ministry. Almost all projects are planned in or around medium-sized cities. To accommodate the construction of these houses, city densities are likely to increase as well as the average building height.

At the same time, our sustainability goals demand that the houses that we build must be highly energy efficient and must provide a healthy, comfortable indoor environment. Fortunately, the ambition to make our built environment more environmental-friendly conspires well with the ambition for 1 million homes before 2030. The ‘building code 2012’ (Dutch: Bouwbesluit 2012) is in place for all new construction and transformation projects. All new construction projects must be compliant to the Building Code 2012 by law, which is called the ‘Housing Law’ or ‘Woningwet’ in Dutch. The aim of the Building Code 2012 is to provide lawful guidelines regarding safety, health, useability, energy efficiency and environment (Bouwbesluit, 2012). The Building Code 2012 is a powerful tool for the ministry to increase the sustainability of the built environment, as well as general building performance.

In the near future, the Building Code 2012 will be replaced by a renewed housing law ‘besluit bouwwerken en leefomgeving’ or ‘decree for the built environment’(in short BBL). The BBL will replace the Building Code 2012 per the 1st of January 2024.

Not only is the BBL a lawful change but it also proposes a new method of assessment for daylighting performance. The BBL will adopt the European standard EN 17037 as the methodology for determining daylighting performance, as a replacement for the now-used NEN 2057 methodology (NEN, 2011). Unlike with the older NEN 2057, the positioning of daylight openings is of influence on performance, as well as the shape of the space behind the façade. The EN 17037 (2022) makes use of the daylight factor (DF) metric, which was not a mandatory requirement previously in the Netherlands. The idea behind this change is to have a better representation of daylighting performance and better integration with other European countries and building certificates such as LEED (USBGC, 2012), BREEAM (2023) and WELL (2020). This together should result in better daylighting design, improving the quality of our building stock.

Although daylighting performance according to EN 17037 is a better representation of real-life performance than the current NEN 2057 methodology, the EN 17037 has its limitations. Urban context is not considered when determining the daylight factor, therefore sufficient daylighting in dense urban areas is not a guarantee. Currently, external obstruction does not play a role in daylight assessment, only in evaluation of view and glare probability. The two latter do not have requirements in the Building Code 2012 or in the BBL. This limitation of the EN 17037 can create a situation where real-world daylighting can be significantly worse than in simulation, ensuing in an increase in energy consumption and a penalty on the wellbeing of its occupants.

However, in locations where urban context is of less effect on daylighting performance, the change to the EN 17037 methodology is a step forward in determining and evaluating performance of building designs. EN 17037 describes a methodology to evaluate performance based on climate data, allowing for climate-based daylight modelling (CBDM) techniques to be applied. This is different from the NEN 2057, which is based on ‘equivalent daylighting surface’ and therefore is not affected by positioning of windows, nor is it affected by climate data. NEN 2057 only considers window surface area of influence, which is not a forthright indicator of daylighting performance (Catalina, Virgone & Iordache, 2011), making the EN 17037 a better methodology to assess performance.

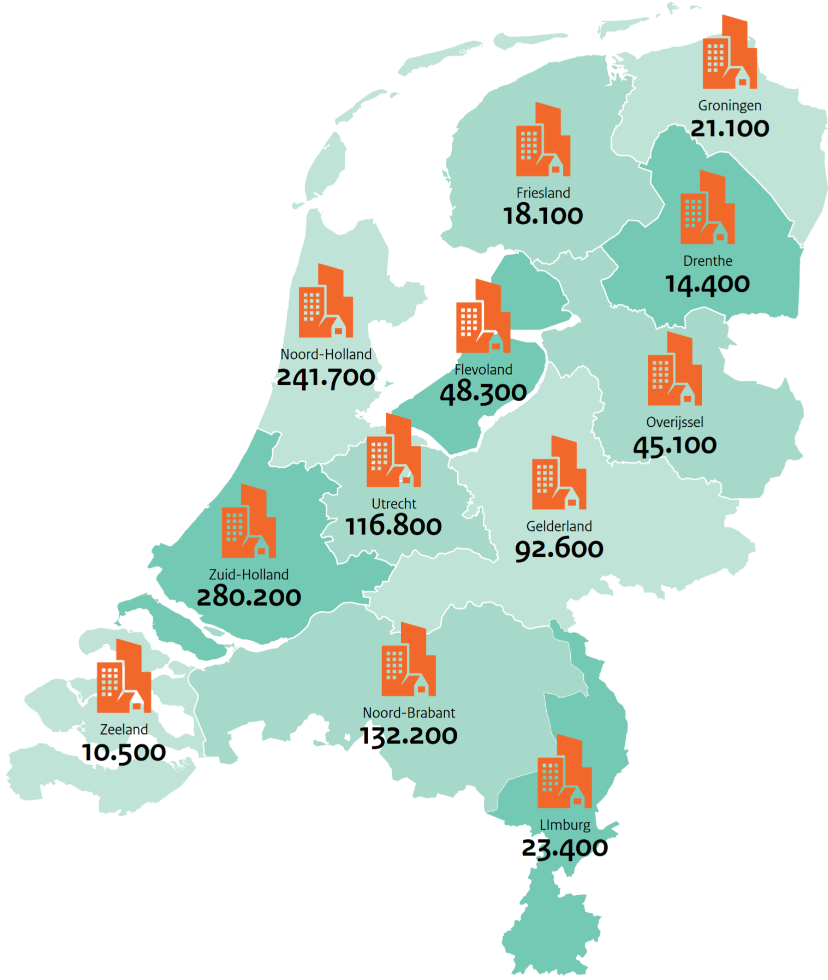


Figure 1: An inventory of building capacity per province in the Netherlands. Indication comes from late 2021. The capacity was 1.044.500 homes before 2030 (ABF, on behalf of the Ministry of Housing & spatial order, 2022).

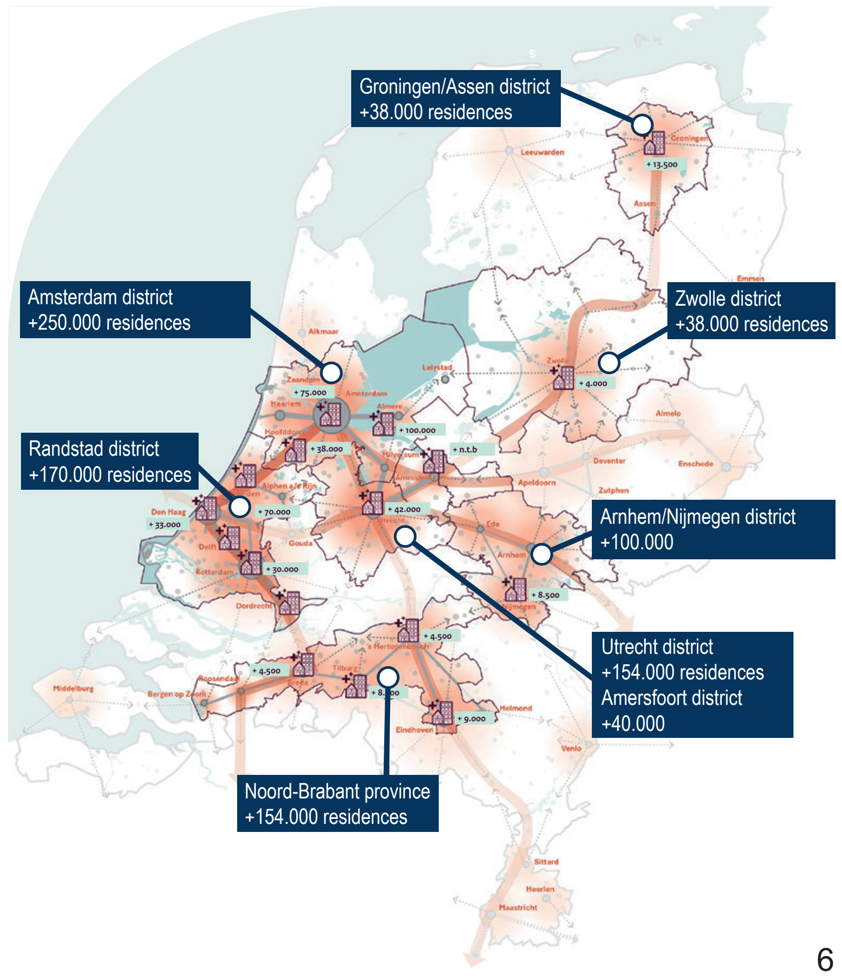


Figure 2: Seven major areas to build 900.000 homes before 2040. Final numbers are being adjusted at the time of writing. Illustration edited for this study, original by the Ministry of Housing & spatial order (2022).

Research gap & problem statement

The problem of EN 17037 not considering urban context in determining daylighting performance arises mostly in areas when urban context causes large obstruction angles, which is known to have a negative effect on simulated DF metrics (Li et al., 2006). It is also known to have a negative effect on simulated energy performance in cold climates (Nebia & Tabet Aoul, 2017). However, when applying for a building permit compliant to Building Code 2012 or the BBL, the obstruction of other buildings is not considered. For this reason, it is impossible to adequately ensure daylighting performance for buildings in high-density areas with solely the methodology of EN 17037 as applied in the Building Code 2012. It remains the designer's or builder's own responsibility to ensure healthy indoor conditions when building residences in dense urban areas.

Therefore, it is unknown what the relation between daylighting performance and urban density is for Dutch urban context. Urban density can be expressed using a variety of indicators, yet there has not been sufficient research on which urban indicators are associated with daylighting performance to inform design improvements.

Finally, the health benefits of daylight are linked to the visible range of the light spectrum in most studies but for non-visual effects studies the circadian sensitivity of the eye should be considered. The circadian effective range of the light spectrum is more sensitive to shorter wavelengths than the visible range of light. The relation between daylighting exposure and health benefits is therefore dependent on the provided daylight spectrum and transmission/reflectance properties of the built environment. It remains unknown if BBL-compliant buildings provide sufficient exposure to circadian-effective light and what impact the built environment has.

In conclusion, it is unknown if daylighting performance is sufficient for residences in urban areas when the EN 17037 is adopted in the BBL. It is unexplored what the impact of urban context is for the Dutch environment. Adding to the complexity, daylight does not only impact visual comfort; it also has an impact on the wellbeing of humans by entraining the circadian rhythm and its aftereffects. Therefore, research is necessary to not only understand the effect of urban context on photopic light but also on circadian-effective light and how to improve it in our designs.

In order to solve the main problem of this research, it is split in different sub-problems to be considered.

1. It is unknown what the performance penalty on daylight is if urban context is included in daylighting simulation. Both static and dynamic simulation needs to be performed to estimate a performance penalty for different urban densities.

2. Relevant for urban areas, it is unknown what the daylighting performance is with an obstructed environment considering different density conditions. It needs to be examined if there are specific density indicators that correlate with daylighting performance.

3. Dutch building regulations regarding daylight are based on photopic illuminance metrics but there are no regulations on circadian illuminance metrics. It is therefore unknown what the non-visual performance in our buildings is and how it may affect our wellbeing.

4. It needs to be investigated what effective design strategies are to avoid bad daylighting conditions: on urban scale as well as on building scale. And in the situation where we find insufficient daylighting conditions, what an effective improvement strategy would be.

Research questions

This thesis will give answer on *what the design consequences are in Dutch urban areas when context is integrated in current daylighting evaluation methods, regarding visual and non-visual levels of daylight.* It will do so by performing literature research on the two functions of daylight and simulation of standard residences in the built environment. To give a complete picture, multiple sub-questions are answered throughout the thesis. The sub-questions are:

1. Which daylighting metrics are currently used to evaluate daylighting performance, and what is sufficient performance for buildings in a Dutch urban setting?

2. What is the relation between daylighting performance and urban density in Dutch context, and how do density indicators correlate with performance?

3. What is the impact of varying reflectance values on daylighting performance, regarding interior and exterior faces?

4. What is the status quo of the health and wellbeing of humans in urban context, regarding non-visual light exposure in a standard residence?

5. How can we ensure daylighting performance in urban residences with different design strategies, both on urban scale and on building scale?

Objectives

This research is about finding an appropriate method to incorporate urban context in current daylighting requirements and to assess its effects on visual and non-visual light exposure. The proposed method of integration is compatible with the future daylighting assessment method: the European norm EN 17037. Openly available data on urban density and the built environment will be employed to determine which locations are representative for the urban landscape in the Netherlands, and different indicators are evaluated for their ability to inform the daylighting performance of a standardized residential building.

Dividing the main objective in sub-objectives gives more definition to the thesis. The sub-objectives for this research are:

1. To define daylight performance and what sufficient visual & non-visual light is, based on current research.

2. To select a handful of urban areas that are considered representative for the urban landscape in the Netherlands.

3. To simulate daylighting metrics that accurately express performance in urban areas, allow for comparison and are suitable for basic statistical analysis.

4. To analyse the sensitivity of reflectance values on daylighting performance, for both interior and exterior faces.

5. To evaluate non-visual light exposure in a standard residential apartment and to assess the effect on our health and wellbeing.

6. To recommend a design strategy that can help improve daylighting performance in urban areas. This will be done on an urban scale as well as on building scale.

Scope

The results of research on daylighting performance can be vastly different for various climates, locations and building designs. Therefore, the scope of this thesis and different boundary conditions are described.

The general purpose of this thesis is to answer the main research question by exploring what the design consequences are if context is integrated in current assessment methodologies. To limit complexity and given the timeframe, two residential buildings are evaluated. The number of residential types is limited, and interior layout is eventually simplified in the simulations ran. The buildings are compliant to the Dutch Building Code 2012 on all relevant aspects. No shading devices (e.g. sunscreens or venetian blinds) are modelled to avoid simulating complex control systems and to keep results comparable.

For all daylight simulations, location 'Amsterdam Schiphol airport' (52.30958, 4.76303) is used to collect climate data from. Climate differences within the Netherlands are small, so no large discrepancies are expected between different locations. The EnergyPlus Weatherfile (.epw file) is retrieved via the EnergyPlus website, using data from an IWEC2 source (ASHRAE, 2001).

For static and dynamic daylighting simulation, Radiance is used in a Rhino/Grasshopper environment. Static simulation is run under CIE standard overcast sky. Dynamic simulation, or climate-based daylighting modelling (CBDM) is assessed over a full year with climate data from ASHRAE's IWEC2 source (2001).

The geometry of the urban context is derived from openly available databases, published by TUDelft3D (2023) in an online environment. The geometry data is a combination of point cloud data from AHN National Height Model of the Netherlands (AHN, 2019) and BAG Register of Addresses and Buildings (BAG, 2022) to create 3D geometry.

The focus of this thesis is to better understand daylighting performance in situations where daylighting is considered insufficient. This means that other important design aspects, such as glare, overheating potential and energy efficiency are not debated to their full extent.

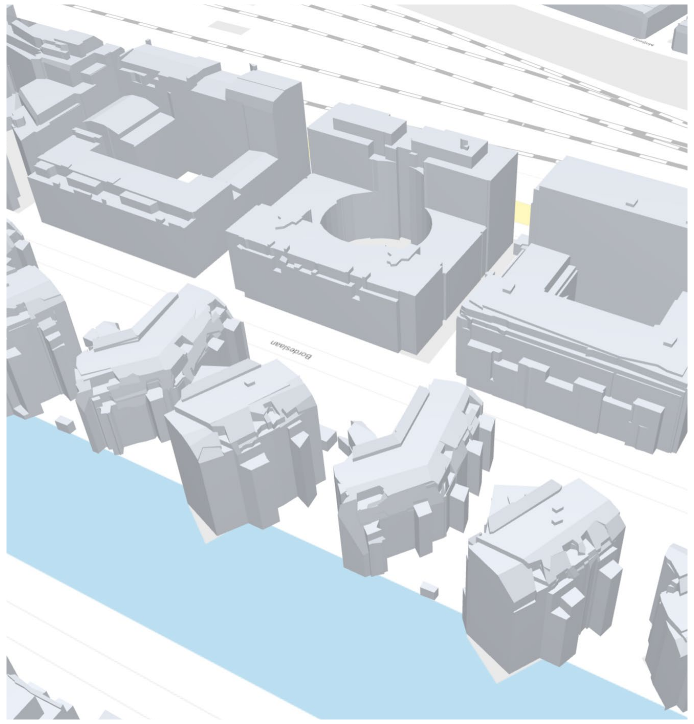


Figure 3: Example output of geometry from 3D BAG (2022) by TUDelft3D (2023). The location is Paleiskwartier in 's-Hertogenbosch.

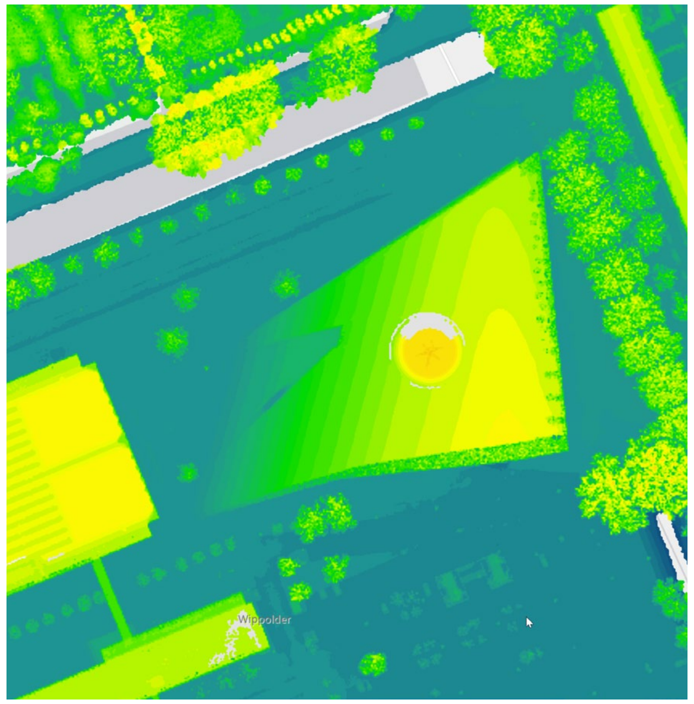


Figure 4: Example output of the AHN4 database (2019). The location is the TU Delft library with a sloped green roof.

Relevance of the research

Societal impact
Modern architects face the challenge of designing more sustainable buildings as well as ones that perform better and are affordable. However, not always are different building requirements in accordance with each other. In case of the topic of this thesis, better daylighting conditions have lead to higher energy consumption and lower thermal comfort in the past. The average glass surface area of a residence tends to have been decreasing in the past years, resulting in debatable daylighting performance in practice.

The result of this trend is insufficient daylighting conditions in newly built residences, especially in the urban environment. Urban context is not considered in current assessment methodologies, resulting in significantly lower performance in the real world than calculated in the simulation models. This might lead to an unhealthy and energy inefficient building design with the residents carrying the trouble.

It is important that our daylighting design provides our bodies with sufficient visual and non-visual stimulus. This increases our health and therefore our wellbeing. This thesis will do research on the current state of daylighting conditions in a realistic residence in different urban environments, and it will propose improvement strategies if performance is found to be insufficient.

Scientific impact
Existing research on the impact of urban context on daylighting performance is often simulating with infinite urban canyons and focussing on photopic performance only. This thesis is trying to generate more information on simulation performance with real world geometry and reflectance values, straying away from hypothetical situations and more towards a realistic setting. Also, melanopic performance is assessed in relation to existing urban context, using two novel metric: melanopic autonomy (MA) and melanopic isotropy (MI). Lastly, daylighting performance as a function of urban density is analysed which has led to interesting results on a potential correlation.

Approach & methodology

All research questions can be answered with literature research, simulation or a combination of both. The main body of the study is about executing the different simulations, assisted and complemented by the literature.

Research and the gathering of in-depth knowledge has been the focus between the P1 and the P2 presentation. The first and second research questions have been answered through literature research in this time period.
The third research question is answered shortly after P2 and helped in better understanding of daylighting simulations and its sensitivity to parameter values.
The fourth and fifth research question can be best answered after most of the simulation work has been done. An analysis with regards to melanopic exposure will be performed to answer research question 4, and results from the evaluation and discussion will lead to the answer of research question 5 and the main research question.

An important motivation of this study is the change in daylighting regulation for the Netherlands. Hence it is important that the results of this thesis can be interpreted in the context of the upcoming assessment methodology in the Netherlands: the EN 17037 (2018). Where possible (and sensible), the methodology of the EN 17037 is the starting point for all simulations run. Aspects that are exclusively applicable in the Netherlands (i.e. Chalkline method and prescribed reflectance values) are not considered any further in the results but they are discussed at the end of this thesis.

Thesis outline

The thesis content is split in 10 sections. They are split in multiple chapters to focus on different aspects of the graduation topic.

The first section 'Introduction' is explaining the problem that lead to the main research question. The objective and scope of the research is discussed as well.
In the second section 'Background - urban context' the most relevant research results on the relation between urban context and daylighting performance are seth forth.
In the third section 'Background - daylight' the relevant knowledge on daylighting and daylighting exposure is presented, explaining the function of daylight as well as the daylighting requirements of humans according to literature and different building codes.
In the fourth section, 'Research methodology', the design and outline of the research is explained. It includes detailed information on the different urban locations that are assessed, the residential buildings in the simulation models and the settings/metrics that have been used.
In the fifth section 'Research results' an overview of discriptive results is discussed as well as in-depth analysis of the gathered simulation results. The results are split to type of simulation, urban density and scale level.
In the sixth section 'Discussion', recommendation are made to improve daylighting conditions for residences in dense urban areas. The most effective mitigation strategies and most important lessons learned are highlighted.
In the seventh section 'Conclusion' the common thread of the thesis results is emphasized and set out. The research questions are answered and it marks the final formal section of the graduation thesis.
An insight to the graduation process, the used references and additional results data can be found in sections 8 to 10.

background - urban context

Daylight in urban context

The interaction between the urban environment and daylight is not unexplored: it is known to negatively affect daylighting performance in residences, offices and even on street level. Not only daylighting is affected but buildings can also cause view obstruction and can block direct sunlight of entering a room altogether. Although we can make recommendations to avoid these problems (EN 17037, 2018), it still is a challenge to find a good balance between all factors that can influence daylighting performance in the urban environment.

In Europe, daylighting performance is assessed either via national norms (i.e., the NEN 2057, 2011) or via the European norm, the EN 17037 (2018). The EN 17037 is an assessment methodology developed for designers of buildings to assess their buildings for good daylighting conditions. The norm touches on daylighting aspects such as illuminance levels, view, sun lighting and glare. The norm is focussing on the performance in the interior, so context is generally disregarded unless specified otherwise (i.e. with sun lighting and view assessments). However, it is relatively unknown how urban context affects performance on these topics throughout Europe. The effect of the urban context on daylighting access will be assessed in this thesis.

Daylight factor and the urban context

An important aspect of the European EN 17037 recommendations is that its requirements can be hard to achieve depending on the geo-location of an assessed building. Research by Sepulveda et al. (2022) has found that it is harder to fulfil the norm's daylight factor (DF) requirement in higher latitudes. They found this through simulation of a standardized building in all capital cities of the EU. The reason for this is because the EN 17037 recommends a minimum illuminance threshold of 300 lx on the work plane, resulting in a higher DF requirement for northern countries with lower median external diffuse illuminance levels (EN 17037, 2018). It is possible that in building design, more glass surfaces must be created to meet recommendations, lowering the average insulation value of a building's façade. Especially for colder climates, this seems to clash with our ever-increasing demands for energy efficiency.

But with obstruction surrounding a building, it is almost certain that DF requirements become even harder to fulfil. There has been limited research on how much performance decreases in real urban setting.

Daylight as a function of urban density

Literature shows that the strongest relation between urban density and daylighting exposure is expressed using the floor-space index or the Floor-area ratio (FSI/FAR, meaning is explained in detail on page 12). Recent research by Sprah & Kosir (2020) has explored what the maximum room depth can be, given a hypothetical urban environment. The DF requirement was identical to the EN 17037 daylight factor requirement for Slovenia. Site coverage was also investigated but suggested a weaker correlation with daylighting performance. Sprah & Kosir did not express the correlation between FSI and daylighting in numbers but merely saw a trend in Figures. However, they concluded that it is possible to link urban typology & density to daylighting performance.

Meanwhile, Bournas & Dubois (2019) performed research on EN 17037 compliance in the Swedish context. They have simulated 10888 real-world residences in multiple areas of Stockholm and assessed their performance for multiple daylighting metrics. Their most relevant conclusion is that daylighting performance (according to EN 17037) of real-world residences show a medium-strong inversed correlation with the FSI of a building site (R^2=-0.635). Further analysis on the data generated by Bournas & Dubois (2019) presented that for Stockholm context, EN 17037 method 2 is more favourable that method 1, a phenomenon that is also visible in the data of this thesis.

Pan & Du (2022) also assessed real-world daylighting performance: they measured illuminance outdoors on street level for Chinese context. They measured the daylight exposure in multiple parts of Shenzhen City under sunny conditions. They did not use the same performance metrics nor did they run any simulation; hence they express daylight performance as total annual illuminance (TAI). In conclusion, they did not find a correlation between urban density indicators and daylighting performance. However, they did find a strong correlation between sky view factor (SVF) and daylighting exposure (R^2=0.858), suggesting that point-level indicators might be more suitable for daylighting assessment than site-level indicators (Pan & Du, 2022).

Point-level indicators

The Sky view factor is commonly used in research on urban heat islands, outdoor thermal comfort and radiation studies. It expresses the percentage of the sky dome that is visible from a point. In the horizontal plane, the maximum value is 1,0 meaning the whole sky dome is visible. Measured on a vertical plane, for example a façade, the maximum value is 0,50, because only half the sky dome can be seen. The SVF is linked with daylighting performance but more often the angle of obstruction (AO) is used. The angle of obstruction is a two-dimensional expression of obstruction, making it simpler to work with in hand calculations and easy to understand. However, with complex daylighting simulation becoming more accessible, the three-dimensional SVF is used more often nowadays.

Earlier studies on AO and SVF in relation to daylighting performance have found convincing results. A study by Li et al. (2006) had found that DF performance can be decreased by as much as 70%, solely by increasing the AO in a hypothetical infinite urban canyon. The performance was only assessed for daylight factor metrics; thus, orientation and climate data are not considered. Though this research does not reflect real urban characteristics, it highlights the potential of an 'obstruction indicator' in relation to daylighting performance.

Lopez et al (2016) had verified that SVF is a suitable predictor for daylighting performance in their research. Their hypothesis was that when SVF is measured in a location, a change in SVF can be used to estimate a change in daylighting performance. They have done this for a hypothetical project in Switzerland and simulated the DF performance on street level. In conclusion, they found that the simulated performance change between the existing and hypothetical situation is consistent across multiple levels, meaning that SVF is strongly correlated with DF performance in outdoor conditions. Although Lopez et al. (2016) did not give any sensitivity coefficient to this change, it is clear from their graphics that SVF correlates with daylighting performance on street level.

More recent research on the relation between obstruction and daylighting performance is often approached holistically. Chen et al. (2016) made use of the angle of obstruction (AO) in their research on indoor environmental quality (IEQ) improvements. They assessed a standard residential building in Hong Kong and performed a sensitivity analysis for all building parameters, including the AO. When optimising for daylight performance, they found that an AO value of 11.1 degrees is the Pareto optimum, which would translate to a wall of ca. 2m height at 10m distance, or a three-story building at a distance of 46m. Chen et al. (2016) had found a sensitivity coefficient (SC) of the AO value on daylighting performance is negative, meaning that daylighting performance is decreased with an increase in AO value (SC=-0.45). On thermal comfort performance, the SC is positive, meaning that thermal comfort is generally improved with larger obstruction (SC=+0.28). This is probably due to less overheating, although no conclusions are made by Chen et al.. In conclusion, Chen et al. (2016) found that with all building parameters, daylighting performance correlates negatively with thermal comfort. This means that daylighting performance cannot be regarded separately from thermal comfort, presumably due to overheating issues. This is especially the case when a change in solar heat gain coefficient (SHGC) is applied: the SC of the SHGC on daylighting performance is positive (SC=+0.52), whilst the SC on thermal comfort performance is negative (SC=-0.75).

Daylighting and overheating

Daylighting performance cannot be regarded separately from thermal comfort, since (direct) sunlight can cause overheating issues or a lack thereof can increase heating demand in the winter. Chen et al. (2016) confirmed this and observed that a change in solar heat gain coefficient (SHGC) has a positive effect on daylighting performance (SC=+0.52) but with reduced thermal comfort (SC=-0.75). This trade-off is known for longer but becomes increasingly relevant due to our ambitions for a more sustainable built environment and smarter use of energy.

Nebia & Aoul (2017) did research to the relation between overheating and daylighting in London high-rise buildings. For four levels, they assessed different apartments in a standard residential tower. Looking separately at daylighting performance and overheating (energy) performance, they concluded that excessive solar gain is the main reason for overheating in residential buildings. Overheating can be mitigated with a different ventilation strategy but a significant conflict between daylighting performance and overheating remains. Dynamic solar shading can be solution to this problem but possibly results in a higher space-heating demand (Skarning et al., 2017).

In conclusion, adequate daylighting in urban context is a challenging aspect of building design, especially taking overheating and urban density into consideration. The EN 17037 (2018) is an assessment methodology for good daylighting conditions but does not consider real-world context that is known to affect DF performance.

The degree of correlation between urban density and daylighting performance is a topic of interest in multiple papers and seems convincing for most of them.

Stronger indicators of DF performance are point-level indicators such as the sky view factor (SVF) or angle of obstruction (AO). The relation of point-level indicators and DF performance is certainly positively correlated but definitive SVF and AO values might be hard to calculate in early design stages (i.e. without a digital model). Therefore, point-level indicators are not optimal for predictions in early design stages but rather useful for later design stages.

Lastly, daylighting performance in urban areas is often linked to overheating issues and an increase in energy demand. Daylighting performance cannot be regarded separately from the two. Research shows that excessive solar gain is the main reason for this but solar shading can provide a possible solution.

Though the focus of this research is on daylighting performance in urban areas, it is important to understand that building performance on other aspects is touched upon as well.

Urban density indicators

The human ability to recognize and explain differences between urban areas is a subjective practice but not solely impressions can be used to distinguish two cities from each other. Especially useful in research, descriptive characteristics can help to recognize discrepancies immediately and can therefore quantify our designs (Berghauser-Pont & Haupt, 2004).

Berghauser-Pont & Haupt (2007) described urban density with four main indicators, and graphically summarised this in their book "*Space mate: the spatial logic of urban density*", which was published in 2004. They suggest that the Spacemate graph can help in describing performance differences in urban areas with distinctive characteristics. The indicators that they plot in the Spacemate are the floor-space index (FSI, also known as FAR), the ground-space index (GSI), the open-space ratio (OSR) and average layers (L). The definition of these metrics are shown in Figure 5.

In the past, urban density indicators were quotients with the total area of land as denominator. However, this does not always explain the spatial differences between two cities (e.g. building typology is not expressed as a function of total area of land). The FSI, GSI, OSR and L do have various denominators, allowing them to indicate a specific spatial characteristic. The FSI measures the building intensity in an area, where a high value means a lot of indoor space is present in an urban patch. Therefore, intensity means the ratio of built surface area compared to the total surface area. The GSI measures the compactness, where a high value means that buildings are close distance to one another. The OSR expresses the spatial openness of a location, not only regarding ground floor space of buildings but also the intensity of those buildings. Lastly, the number of layers (L) is a better-known indicator, and it expresses the average number of floors of buildings in an area.

All four indicators that are charted in the Spacemate can be measured and calculated on various scales. An example of the spacemate is shown in Figure 6. On the smallest scale of a single building plot, the indicators describe the characteristics of a single building or a single project, and value differences can be large between adjacent building plots. Looking at a larger scale, for example on city district level, the indicators become useful in comparing different parts of a city and show a more gradual difference. The Spacemate helps to quantify the urban density differences without the disadvantages of more subjective methods.

Calculating and measuring these urban density indicators on various scales allows us to categorize the urban landscape. An application of the Spacemate can be to get a complete (graphical) picture of the different urban landscapes that are present in a greater area. By plotting an urban patch on the Spacemate, a researcher or designer can visually link it to other characteristics. A hypothesis could be that urban areas with similar density indicators perform the same on various aspects, for example in terms of urban heat island effect, air quality, average housing rent and daylighting.

Another use for the Spacemate, and the urban density indicators in general, can be to recognize where future densification is possible. The Netherlands needs to build one million homes before 2030 but there needs to be physical space available. Ideally, these homes can be built in places where density indicators like the OSR and GSI have high and low values respectively. However here, large differences can be observed between adjacent patches, which can cause discrepancies if the patch scale does not fit the research.

Interlinking this to research on daylighting performance in Dutch urban areas, a suitable scale to extract urban density data from would reflect density of the surrounding buildings, as well as being representative for urban density on a larger scale (homogeneous environment). It should also be able to include a level of detail (LoD) to which subjective urban characteristics be linked, such as openness and liveability.

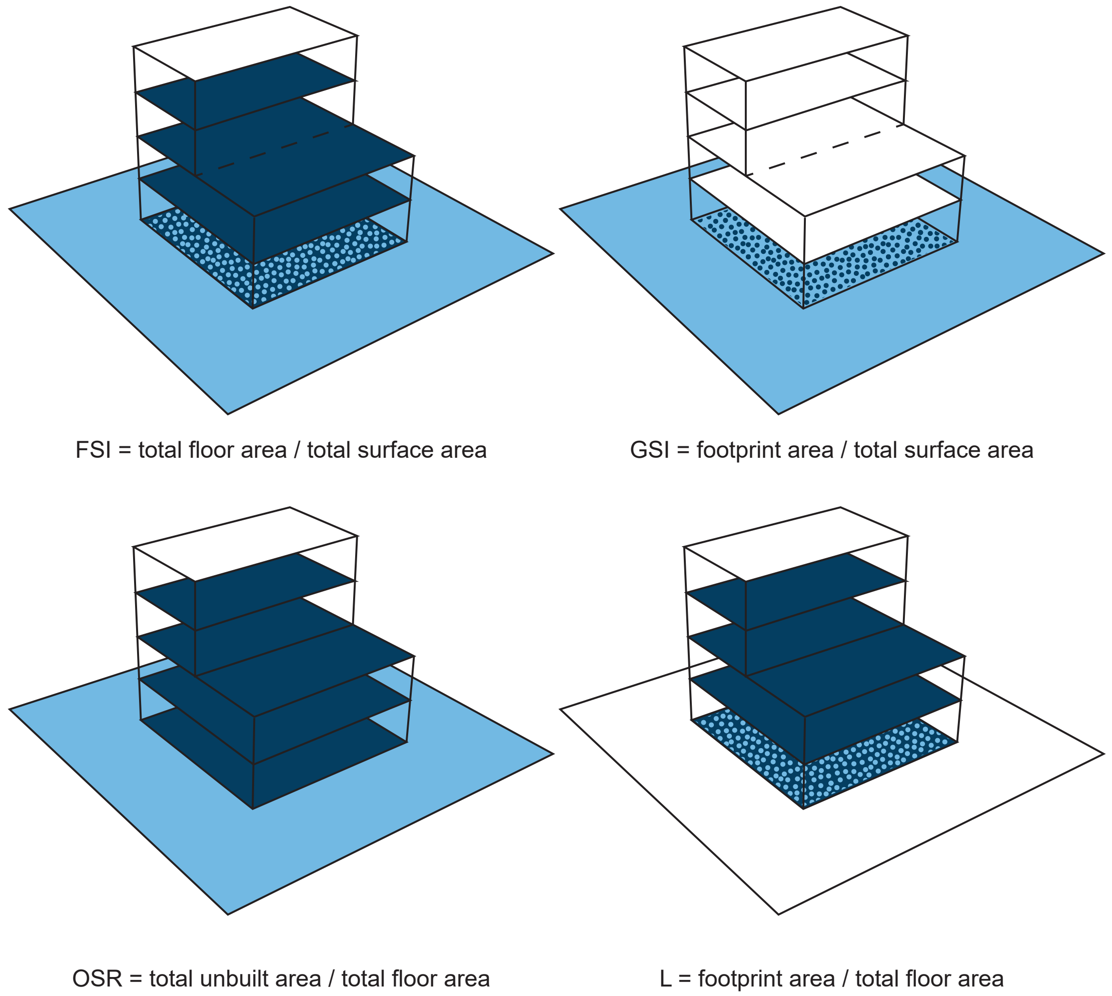


Figure 5: The definitions of different urban density indicators, used by Berghauser-Pont & Haupt (2007) in their Spacemate diagram. Own source.

Rather than calculating values by hand, urban density data is calculated on various scales by the Netherlands Environmental Assessment Agency (PBL) and is called RUDIFUN-data (abbreviation of Spatial Density and Function-mixing in Dutch). First published in 2019 and updated in 2022, the PBL (2022) makes use of publicly available data of the built environment (PDOK, 2022; NWB, 2022; BAG, 2022) to calculate various urban density indicators, including all the indicators that are in the Spacemate. The densities are calculated for the scales: municipality, district, neighbourhood and building block. All scales use either net or gross data, excluding or including public space respectively. Scales that are particularly interesting for this research are the gross building block and the gross neighbourhood.

The scale of the gross building block derives its density data from a set of adjacent buildings. Therefore it produces weighted average density data. In gross data, public space is included such as streets, city squares and waterways. If public space is in between two building blocks, it gets split in half. This means that a similar building block on a boulevard gets lower-density values than if that building block was to border on a narrow alley. Gross building blocks are always adjacent to one another, creating a larger patch (up to one gross neighbourhood).

The gross neighbourhood scale consists of the sum of all gross building blocks within the neighbourhood borders as determined by the CBS Statistics Netherlands (CBS, 2022) and BRK Netherlands cadastre register (BRK, 2022). The difference in urban density is more gradual on gross neighbourhood scale compared to the gross building block scale but still shows significant distinction.

For research on daylighting performance in Dutch urban areas, the data on gross building block is most important. It encapsulates the density differences within the gross neighbourhood scale without the large discrepancies of the gross building blocks. To check if a selection of gross building blocks is representative for a larger urban patch, the gross neighbourhood scale is used for control data. This is elaborated more on pages 22-24.

Reflectance properties

Urban context has an influence on daylighting performance in two ways. First, the built environment is blocking view to the sky, causing an obstructed view. Secondly, the reflectance properties of the surrounding surface area are variable per building (Li et al., 2006). The amount of obstruction can be derived from urban density indicators (higher density usually translates in more obstruction) or directly from an angle of obstruction measurement. However, reflectance values can only be calculated if the materialisation of an urban area is known. Materials with a light colour or high surface reflectance tend to result in better daylighting performance (Li et al., 2006), therefore it is important to include realistic reflectance properties in daylighting simulations with urban context.

In the building industry of the Netherlands, a small number of materials account for the bulk of the annually consumed materials (NIBE, 2019). For finishing materials, masonry is used most often, accounting for 4% of the total weight annually. For reference, all polymer and wood products combined is less than 3% of the annual consumption. This heavy usage of masonry is reflected in our built environment: most facades in the Netherlands consist of masonry and glass surfaces.

In daylighting assessment methodologies, the reflectance properties can have a significant effect on total performance (Brembilla et al., 2018). If urban context is included in this assessment, it requires to have realistic properties. However, a façade consists of multiple sub-surfaces that can vary in reflectance, making calculations of average reflectance values an extensive task. Knowing the sensitivity of reflectance values on daylighting performance would help to speed up this process.

For Dutch context, it is known what the average physical properties are for the most common types of residences. The RVO Netherlands Enterprise Agency (RVO, 2022) is measuring and calculating average physical values for each residential typology per time period. The most recent version they published is from 2022 and includes average values on façade properties, energy labels and typical installations used. Important for this research, window to wall ratio (WWR) can be derived from the data for each type of residential building in the Netherlands. A weighted average reflectance can be calculated for every building accordingly. For non-residential buildings such as offices, no national source on façade properties is available at the time of writing but realistic WWR can be assumed based on photography and field observations.

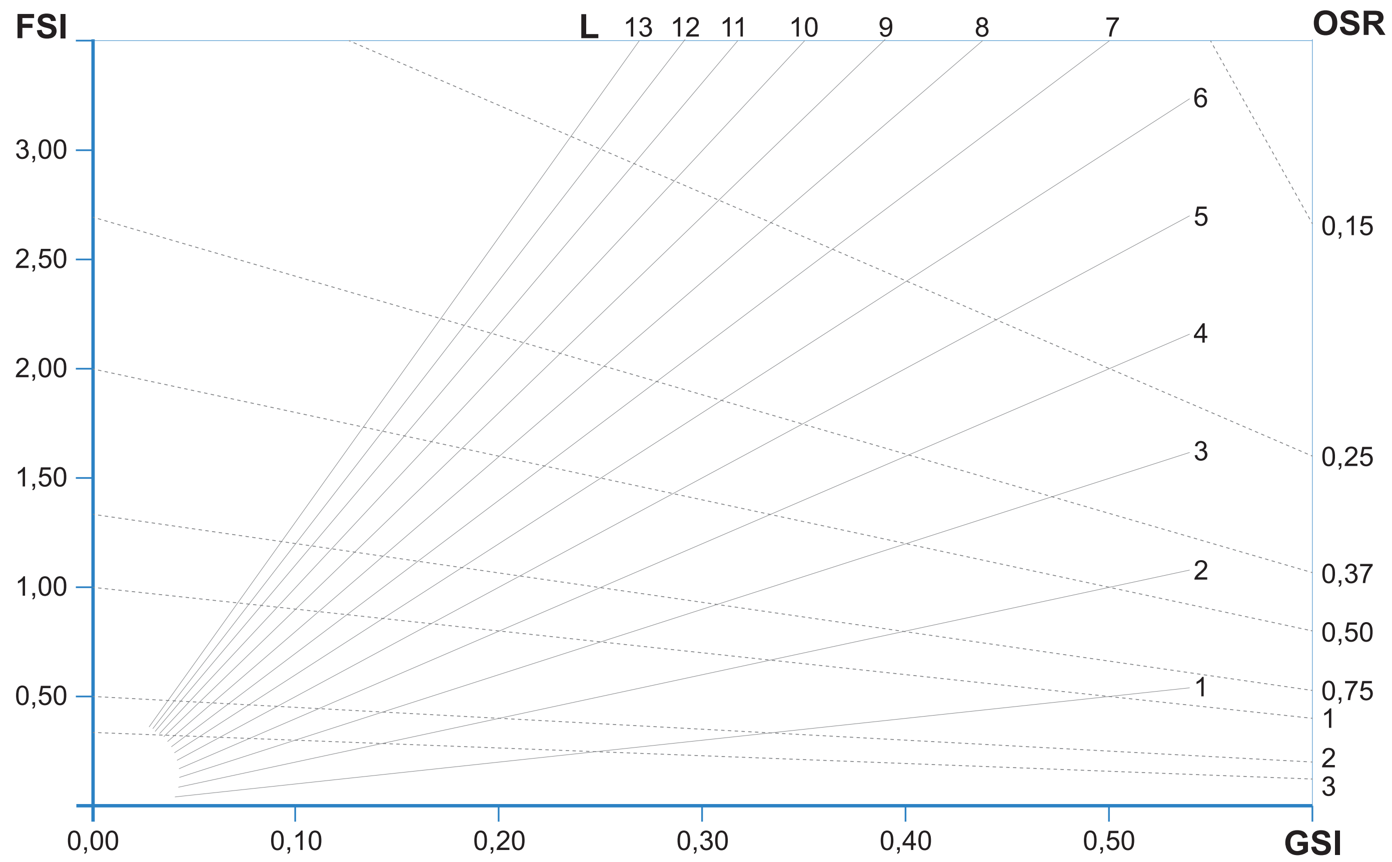


Figure 6: The Spacemate Figure by Berghauser-Pont & Haupt (2004). On the Y-axis is the FSI and OSR value, on the X-axis the GSI and L values. Redrawn by the author. (Original: Berghauser-Pont & Haupt, 2004).


Figure 7: A photograph of typical Dutch apartments with brick facades. Project 'De Weverij' in Tilburg is built in 2023. Own source.

background - daylight

Functions of daylight

Daylight is an important aspect of human wellbeing. Not only does daylight provide us the ability to see indoors but it also has chronobiological effects on our body that benefits our health. Hraska (2015) calls this the visual and non-visual functions of daylight. Although the sun emits wavelengths from 200 nm and up, the human eye is only perceiving wavelengths between 380-780 nm as visible light (Webb, 2006). Exposure to long wavelengths (infrared, > 780 nm) give a warm sensation since the light waves transfer more energy to the skin. Short wavelength exposure (UV/blue, < 380 nm) is linked to other effects, like melatonin suppression in the body (Hébert et al., 2002), skin cancers (Veierod et al., 2003) and mental wellbeing (Nestler et al., 2002): this is called the non-visual effects of daylight on the body. However, this was not known prior to the discovery of a non-visual photoreceptor that is mostly sensitive to short wavelength light (Brainard et al., 2001).

Two functions of daylight
Before the discovery of the non-visual photoreceptor on the retina, Boivin et al. (1994) had find that circadian rhythm can be influenced by adjusting exposure to light. They did not consider the spectral power distribution (SPD) of the source to be a factor. In their research, they found an illuminance value of 1260 photopic lux to be of positive effect on human alertness, and they were able to shift the circadian rhythm of their subjects. However, the 1260 photopic lux threshold is a high illuminance level for indoor environments, and in hindsight does not express how much circadian effective light is emitted in the test environment. More research was necessary to attest what type of light was most effective for these non-visual effects of light and how its dose-response curve looks like.

Cajochen et al. (2000) also did research on light exposure and the non-visual effects on the human body. They have found that an illuminance level of 300 photopic lux, measured at eye level (vertical plane), is required to have a maximal stimulant effect on relative alertness. This is significantly lower than the threshold value that was earlier found by Boivin et al. (1994). An illuminance level of 23 photopic lux is found the be the lower threshold for minimum stimulation of the human body. Any lower illuminance level did not affect the subjects. Following from these two threshold values, a first attempt for a dose-response curve was made.

Just like in the study of Boivin et al. (1994), they did not consider the SPD of their light source to be of influence but the much lower threshold value for maximum stimulus compared to Boivin et al. (1994) is notable.

In 2001, Brainard et al. had found that melatonin levels, which is strongly regulated by the circadian rhythm (Rollag & Niswender, 1976), are significantly suppressed after exposure to short wavelength light. This result suggests that humans have a photopigment in the retina that is mainly responsible for circadian entrainment and other non-visual effects on the body. The research was performed by exposing 72 subjects to monochromatic light between 02:00 and 03:30 AM. Their blood values were measured before and after light exposure and showed a significant decrease in melatonin levels across all monochromatic light sources ($p < 0.003$). The peak sensitivity was found at wavelengths between 446 and 477 nm. This means that the SPD of a light source can be linked to the non-visual potential of a light source (not all sources emit the same wavelengths of light) and that various light sources can have different influence on circadian entrainment and non-visual effects of the body.

Importance of daylight exposure

The knowledge that short wavelength light and exposure to it has influence on the circadian entrainment and wellbeing of humans, has led to more research to the importance of light in the built environment. It led to the realization that humans need to be exposed to circadian light specifically but research on this topic is relatively unexplored. Quickly after the discovery of the circadian-sensitive photoreceptor, Lockley, Brainard & Czeisler (2003) concluded that photopic lux metrics are not appropriate to determine the effects on the human circadian rhythm. Therefore, a building requirement for a threshold value in photopic lux is not effective to ensure circadian entrainment. This calls for a novel non-visual light metric to express circadian-effective performance of an indoor space.

Evaluating non-visual light performance
To be able to determine the circadian light levels of a space, research by Andersen, Mardaljevic & Lockley (2012) developed a framework that allows us to evaluate this by incorporating ‘circadian potential’ of a space in conventional lighting simulation models. Because peak sensitivity of circadian light is different than that of photopic light (446-477 nm compared to 555 nm), only a small portion of the visible light spectrum can influence the circadian rhythm. This makes the photopic lux metric not useful to determine circadian-effective performance but such metric did not exist yet.

Andersen, Mardaljevic & Lockley (2012) developed a workaround: they found that the SPD of a light source can be multiplied by the circadian sensitivity curve $C(\lambda)$ to get its ‘circadian efficacy’. This can be used to calculate a ‘circadian-equivalent illuminance’ by comparing illuminance levels with the light exposure threshold necessary for maximum non-visual stimulus.

As an illustrative example they compared CIE standard sky D55 (2018) to 4100K polychromatic light as used by Cajochen et al. (2000). In the research by Cajochen et al. (2000) they found a threshold value of 300 photopic lux to have maximum stimulant effect on the human body. Using the framework by Andersen, Mardaljevic & Lockley, this is equal to 190 photopic lux from the CIE standard sky D55. So if a level of 190 photopic lux is achieved in a simulation with a CIE D55 sky, maximum circadian potential is reached. Since the illuminance levels are measured at eye level, the circadian potential can be determined for different orientations in a room.

The approach by Andersen, Mardaljevic & Lockley (2012) requires a circadian-equivalent illuminance to be compared to a known light source, making it not a one-dimensional metric like photopic illuminance that can be calculated or measured directly. Lucas et al. (2014) recognizes this and proposes a new unit: the equivalent melanopic-lux (EML). The EML unit uses the melanopsin response function and is corrected for pre-receptoral filtering. The conversion factor to convert photopic lux to EML directly is different for all light sources but can be calculated independently based on its SPD properties. This allows researchers to use the EML as a one-dimensional unit to compare results.

EML in relation to artificial light and daylight
Since the level of EML is dependent on the SPD of a light source, the circadian effectiveness of artificial light and daylight can be vastly different. For daylight, the EML level can be hard to determine due to rapidly changing sky conditions. Adding to the complexity, photopic illuminance levels can also change quickly, for example under cloudy sky conditions. As for artificial light, the EML levels are more easily determined: Artificial light sources have a constant SPD that can be measured by a spectrophotometer and therefore produce a constant conversion factor. If the photopic illuminance is known, the EML levels can be calculated directly without a time-dependent factor. However, note that if the colour temperature of the light source changes, the SPD and therefore EML output will also change.

Daylighting assessment methodologies

EML in annual simulation and assessment methodologies
Some CIE sky conditions have more favourable SPD properties and can therefore provide more EML. Photopic irradiance has a measured average luminous efficacy ranging from 109 lm/W to 137 lm/W (Li et al., 2008) but the luminous melanopic efficacy is not measured before. It is known that the melanopic efficacy varies per sky condition, which is ideally recorded in the climate data but like photopic luminous efficacy, this data is not directly recorded in weather data. As a consequence, it is possible that an annual simulation for melanopic illuminance exposure is inaccurate due to these changing conditions.

However, contrary to an annual melanopic simulation, a point-in-time melanopic simulation can be performed with more certain parameters resulting in more accurate results. If the photopic illuminance and the sky condition with its corresponding melanopic luminous efficacy is known, an estimation can be made on the performance in a known worst-case scenario. This can be done for example under a cloudy sky with median illuminance conditions (in a regular photopic simulation).

Melanopic metrics in practice
The equivalent melanopic lux-metric (EML) is known to be used in the WELL-being standard (International WELL Building Institute, 2017) but is not yet used in other green building certificates. In the WELL-being standard the EML is measured on the vertical plane to assess the light exposure of the eye. This is vastly different from conventional photopic lux metrics, which are often measured on the horizontal plane. The variation in circadian efficacy per light source, photopic illuminance and plane conversion makes it complex to compare the EML performance to photopic lux performance metrics. To make the comparison between melanopic performance and photopic performance easier, the CIE (2018) has developed a methodology and a new metric. The melanopic-equivalent daylight illuminance metric, M-EDI in short, is a metric that mathematically results in 1000 photopic lux under CIE standard sky D65 being equal to 1000 melanopic lux. By using the $M\text{-}EDI_{D65}$ metric, all light sources can be compared and assessed for their non-visual effect on humans, by using the same reference illuminant.

This does not make the EML metric useless: the framework as described by Lucas et al. (2014) is still used for the M-EDI, only weighed to a standard CIE illuminant. The conversion therefore between EML and M-EDI is linear, using the formula:

$$M\text{-}EDI_{D65} = 0.9058 \cdot EML$$

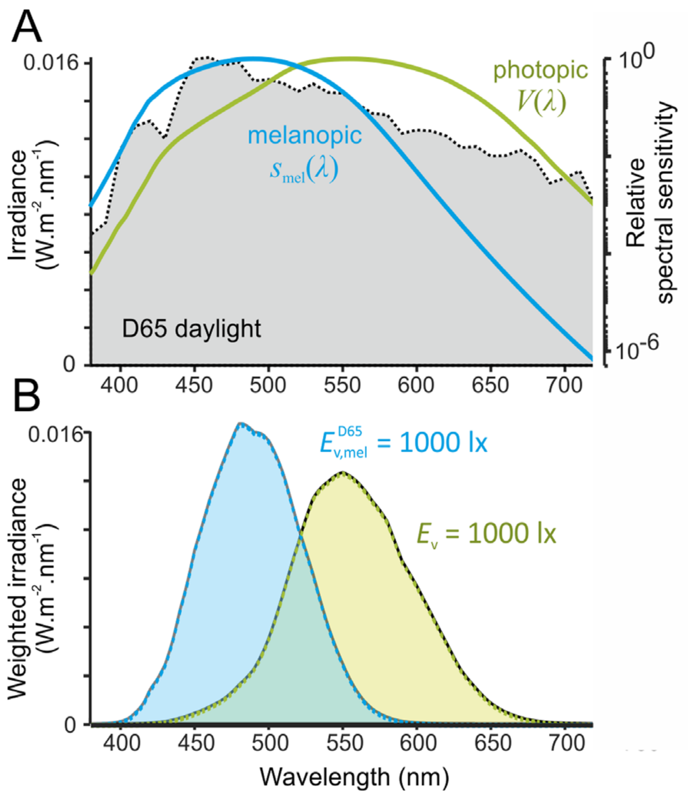


Figure 8.a-b: Differences in photopic and melanopic sensitivity: a Figure created by Brown et al. (2022). Graphic A shows the SPD of CIE sky D65 (CIE, 2018) and the relative spectral sensitivity of the human eye for both the melanopic and the photopic part of the visual spectrum. Graphic B shows the weighted irradiance of the CIE sky D65 for both functions of daylight, mathematically resulting in $E_v = M\text{-}EDI_{D65} = 1000lx$. Original Figure from Brown et al. (2022).

Photopic daylight requirements
Multiple assessment methodologies will be discussed in the next section. In the Netherlands, illuminance requirements in building codes and green-building certificates are referring to photopic illuminance only, unless otherwise stated. In case a daylight factor (DF) metric is used, the median outdoor global illuminance for the Netherlands (14400 lx) will be used in accordance to the European standard EN 17037 (2018). An overview of all requirements can be found in table 1.

EN 17037 methodology
The European standard EN 17037 uses two methods to determine if a design fulfils daylighting requirements. The first method is by evaluating the daylight factor (DF) under standard CIE overcast sky conditions and it has two requirements. The second method is an annual simulation where the daylight autonomy for a minimum threshold is calculated.

With the first method the EN 17037 is recommending an illuminance of 300 lx for a minimum of 50% of occupied space under a CIE overcast sky. The recommended minimum illuminance is 100 lx for at least 95% of a space under a CIE overcast sky. A study by Sepúlveda, De Luca & Kurnitski (2022) has found that the first requirement is more restrictive for side lit rooms in cold climates, so it is expected that only the first requirement is relevant in this research.

The second method is to evaluate the design with an annual simulation by applying a climate-based daylight modelling (CBDM) method. This method is favourable for occupied spaces that have access to direct sunlight (DGMR, 2021). The requirement for illuminance is the same as in method 1 (300 lx for a minimum of 50% of the occupied space). But because an annual simulation has a time dependency, this threshold must be met for 50% of the total sunlight hours (2190 hours per year). Like in the first method, the second requirement is less strict for cold climates, and it is expected to not be an important requirement for this research.

Dutch building code
Currently, the Dutch Building Code 2012 makes use of a unique metric 'equivalent daylighting surface area' (NEN 2057, 2011). The main requirement is that the surface area of the apertures is at least 10% of the gross floor area of that space.

The required percentage of apertures is increased if there are large obstructions i.e. balconies or loggias. There are no requirements or parameters that consider glass type, orientation or climate conditions, hence it is one of the reasons why the NEN 2057 is planned to be replaced in 2024 by the EN 17037 for a more accurate assessment methodology.

The Building Code 2012 is going to be replaced with 'the environment and planning act' (Besluit bouwwerken en leefomgeving, BBL) in 2024. The BBL will use the first method of the EN 17037 but considers different, less restrictive requirements. The minimum DF for an occupied space in residences is expected to be 1.0% for an occupied space and 0.8% for an occupied room (according to the consolidated version of the BBL of 6th of january, 2023 (IPLO, 2023). The distinction between occupied space and occupied area is made to allow for flexible use of space in the future and to be able for occupied rooms to compensate for one another. A rule of thumb is that interior walls are allowed to be 'ignored' when calculating daylighting performance (but structural walls cannot). Both requirements for the area and space need to be satisfied in either a static simulation or an annual simulation.

A unique addition to the interpretation of the EN 17037 in the BBL is the 'chalk line method'. The chalk line method is a way to virtually decrease the size of an occupied space to fulfil requirements, for example for ventilation or daylighting. This is commonly used for attic spaces in row housing but it is allowed to be applied to all occupied spaces, including living rooms or office spaces that might be designed suboptimal. The chalk line method can be applied for up to 55% of an occupied space. In practice, this means the gross occupied area needs to fulfil requirements but for only (50% * 55% =) 27.5%. Combined with the relatively low requirements in the BBL, the chalk line method with the EN 17037 might allow for subpar daylighting performance as mentioned before by DGMR (2021) in a policy study on the implementation of the EN 17037 in Dutch context.

Because the chalk line method considers the gross occupied area, it is project-specific to what extend the chalk line method can be applied. Therefore, it is not regarded any further in the assessment of daylighting performance but rather mentioned in the discussion section. Furthermore, requirements for other building functions are roughly half of the residences. These requirements will not be further discussed in this research since it is not within the scope of this research.

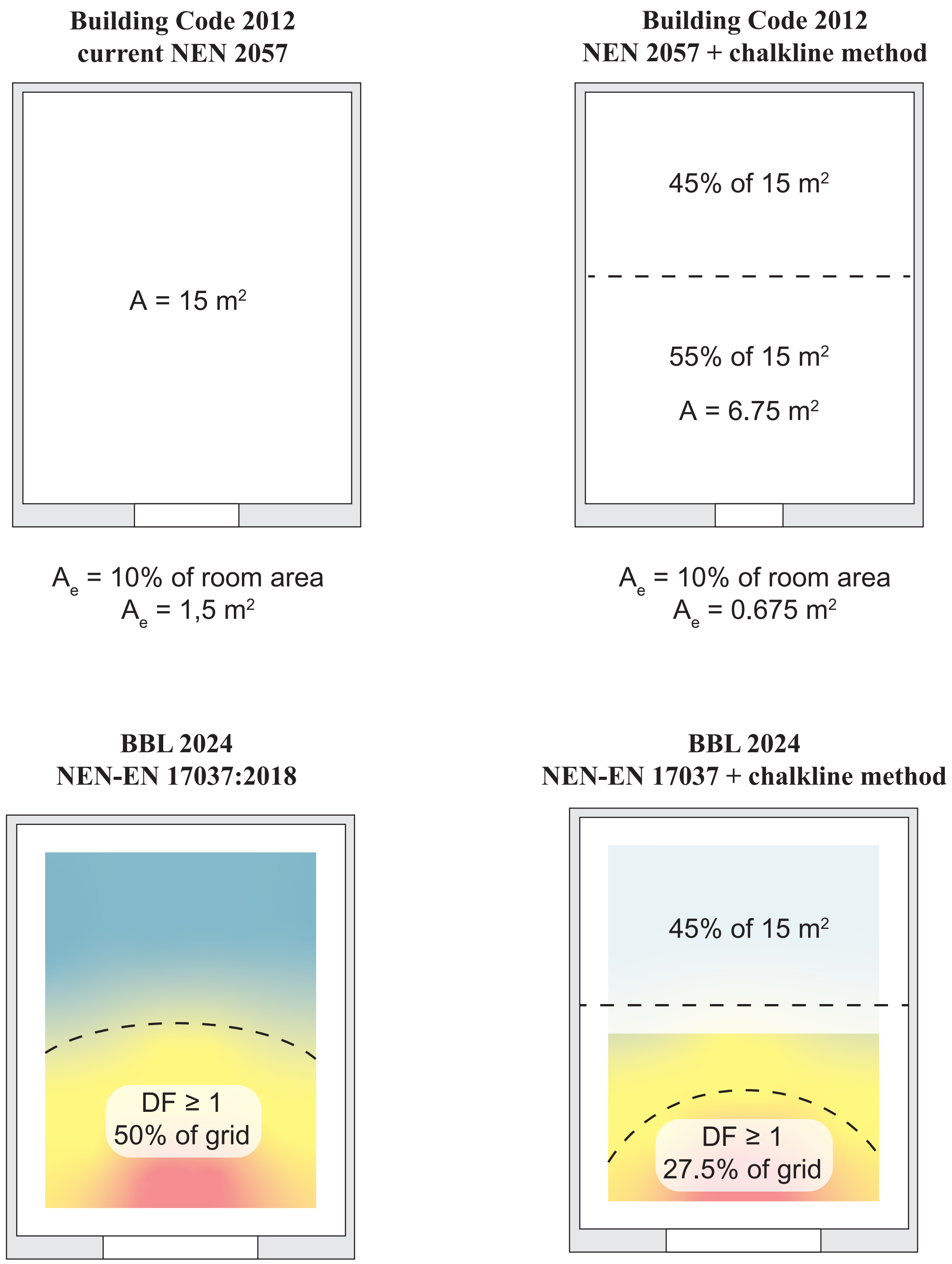


Figure 9: A visual comparison between the differences of the current NEN 2057 methodology and the interpretation of the EN 17037 in the BBL in 2024. Own source.

BREEAM-NL certificate
Based on the British BREEAM certificate, the Dutch green building council has created the BREEAM-NL certificate, adjusted for the Dutch context (BREEAM-NL, 2023). The BREEAM-NL certificate (2014) uses the second EN 17037 methodology in determining daylighting performance but with a different minimum requirement. Their requirement for a residence is a minimum DF of 2.0% for 80% of the occupied space, 50% of the daylit hours. An additional criterion for a BREEAM-NL certification is that a realistic urban area must be considered. This is in addition to the normal methodology of EN 17037, making the BREEAM-NL certificate harder to achieve. The chalk line method cannot be applied for the BREEAM-NL certificate.

Important to note is that the BREEAM-NL certification that is applicable on new construction is the 'New construction and renovation 2014' certificate. The latest BREEAM-NL certificate (2020) for new construction cannot yet be applied because they do not make use of DF, illuminance, or DA metrics but rather the Dutch NEN 2057 methodology as mentioned earlier. With the introduction of the BBL in 2024 it is expected the BREEAM-NL will adopt the DF requirements with the beforementioned requirements.

LEED v4.1 certificate
The LEED v4.1 by the USGBC (2021) certificate considers two methodologies in determining daylighting performance, following the guides of the IES's LM-83-12 norm (2012).

The first methodology uses the spatial daylight autonomy (sDA) of a space. The 'sDA percentage' is the percentage of a room that is at least daylight autonomous for 50% of the occupied time. Daylight autonomous means that a minimum threshold of 150 lux is met but an upper boundary limit of 5000 lux is also of effect, differing from the EN 17037's DA requirement. A level of 10 lx has to be achieved for 90% of regularly occupied floor areas. The minimum requirement to obtain credits is a sDA ≥ 50% (50% of the space needs to be at least 50% daylight autonomous throughout the year).

The second LEED method requires the determination of daylight availability on two set points in time: 09:00 and 15:00 on the brightest day between 16-04 and 28-04 or 16-09 and 28-09. During the two set points in time, $sDA_{150,5000}$ requirements should be fulfiled for 50% of the space. This requirement can only be fulfiled by measuring the performance in a real building.

In the Dutch context, the LEED v4.1 certificate is not commonly used. The standard methodologies that are used for LEED certification are based on Northern American standards, making it hard to integrate with other mandatory assessment methodologies. Thus, the BREEAM-NL and WELL certificates are mostly preferred over the LEED v4.1 certificate.

WELL v2 building certificate
The WELL v2 building certificate (2020) is thought of as the certificate focussing the most on health and wellbeing with research informing the requirements. WELL v2 considers three daylighting options as 'sufficient'. You can either perform an annual daylight simulation, a minimum threshold for glazing area is met or a credit point on 'LO3: circadian lighting design' is achieved.

The first option is performing an annual daylighting simulation. This can either be done with the IES LM-83-12 methodology or the EN 17037 methodology. In this research, the latter will be considered because the IES standard is developed specifically for Northern American countries. The requirement for the EN 17037 method is a minimum illuminance of 200 lx for 30% of the area, for 40% of the annual sunlight hours. This requirement is less strict than the WELL v1 (2020) requirements which did not distinguish commercial buildings from dwelling buildings.

The second option is based on a more simplistic calculation method. The requirement is that the glazing area is no less than 7% of the regularly occupied floor area. This requirement faces the same limitations as the current Building Code 2012. Since this requirement cannot be expressed in a DF, illuminance, or DA metric, this requirement will not be further discussed in this paper.

The third option to fulfil for WELL v2 is to achieve a point in the Circadian lighting design feature. The assessment metric for 'LO3: circadian lighting design' is based on the equivalent melanopic lux metric as defined by Lucas et al. (2014) but WELL v2 also expresses the requirement in melanopic-equivalent daylighting (D65) illuminance ($M\text{-}EDI_{D65}$). The requirements for this are described in table 1.

	$E_{v,d,med}$ [lx]	DF [-]	E_{min} [lx]	$DA_{i,min}$ [lx] for time* [%]	$sDA_{i,min}$ for area [%]	min. Area** fulfilled [%]	static/CBDM
EN 17037, method 1, req1		2,1	**300**	N/A	N/A	50%	static
EN 17037, method 1, req2		0,7	**100**	N/A	N/A	95%	static
EN 17037, method 2, req1		2,1	**300**	**50%**	N/A	50%	CBDM
EN 17037, method 2, req2		0,7	**100**	**50%**	N/A	95%	CBDM
BBL 2024, space		**1,0**	144	50%	N/A	50%	both
BBL 2024, area		**0,8**	115	50%	N/A	50%	both
BBL 2024, space, chalkline	14400	**1,0**	144	50%	N/A	27,5 - 50%***	both
BBL 2024, area, chalkline		**0,8**	115	50%	N/A	27,5%	both
BREEAM-NL (2014)		**2,0**	288	50%	N/A	80%	CBDM
LEED v4.1, option 1		1,0 < 34,7	**150 < 5000**	50%	**50%**	50%	CBDM
LEED v4.1, option 2		1,0 < 34,7	**150 < 5000**	N/A	N/A	50%	static
WELL v2 building, option 1		1,4	**200**	40%	N/A	30%	CBDM

*) Time = total annual daylight hours in the Netherlands.
**) area = gross floor surface area.
***) definitive percentage is project specific.

table 1: Photopic illuminance requirements for residential buildings in the Netherlands. DF and Imin are converted where possible. Original requirements are in bold. (EN 17037 (2022), Building Code 2012 (2022), BREEAM-NL (2014), USGBC (2021), WELL v2 (2020)).

Non-visual daylight requirements

While the industry is familiar with photopic daylight metrics in software packages and lawful requirements, non-visual daylighting requirements are relatively new and only implemented since the introduction of the circadian requirement in the WELL certificate.

Since WELL v2 is a green building certificate that bases its requirements on research and wellbeing of humans, these requirements are based on a paper by Brown et al. from 2022. Based on the $M\text{-}EDI_{D65}$ metric by the CIE (2018), Brown et al. (2022) concluded that during daytime, an $M\text{-}EDI_{D65}$ level of 250 lx is considered sufficient for maximum stimulus of the human body. This is measured as illuminance that falls on the eye (thus in the vertical plane). The collective of researchers held a conference where they compared and discussed the most important research regarding melanopic stimulus in the built environment. Therefore, their recommendation of 250 lx is based on all previous research on this topic. Contrary to providing sufficient M-EDI during daytime, Brown et al. (2022) also stress the fact that M-EDI reduction during the evening- and nighttime is equally important. During evening hours, from 18:00 to 21:00, the maximum $M\text{-}EDI_{D65}$ on the eye should not exceed 10 lx. During the night from 21:00 to 08:00 a maximum $M\text{-}EDI_{D65}$ of 1 lx is recommended, approaching complete darkness.

WELL v2

The WELL v2 green building certificate provides credit points if a design provides 150 EML on the vertical plane at eye height. This value needs to be achieved between 09:00 and 13:00 to provide stimulus during the morning hours. Three points are provided if a level of 250 EML is achieved. The WELL v2 standard adopts the recommendation of Brown et al. (2022) directly. If the interior layout is unknown, as one would expect in a residence, the point of reference is in the middle of the room.

Remarkably, the WELL v2 standard specifies that the EML requirements are achieved by using artificial lighting devices and not by daylighting provision. Presumably, this is because artificial lighting has consistent SPD properties and a continuous luminous flux, making it easier to account for. Also, in the Netherlands and other countries on the same latitude, sunrise can be as late 08:48 in December (KNMI, 2022), making it uncertain that such EML levels can be 'harvested' in the early morning.

However, with using artificial lighting come other aspects such as colour rendering index values (CRI values) and light modulation properties perceived as flickering of the light. Providing the required EML with daylight can therefore be beneficial to avoid possible problems with these artificial lighting systems. This research assumes that achieving the EML requirements with daylight is considered an option but acknowledges that this can be hard, especially in the morning hours and during wintertime.

	M-EDI (D65) [lx]	*position*	*time period*	*plane direction*	*static/CBDM*
WELL v2 building, tier 1	min. 136	middle of room, 1.4m	N/S	vertical	N/S
WELL v2 building, tier 2	min. 250	middle of room, 1.4m	N/S	vertical	N/S
Brown et al. (2022), daytime	min. 250	eye, 1.2m	08 - 18	vertical	CBDM
Brown et al. (2022), evening	max. 10	eye, 1.2m	18 - 21	vertical	CBDM
Brown et al. (2022), nighttime	max. 1	eye, 1.2m	21 - 08	vertical	CBDM

table 2: Melanopic equivalent daylight illuminance (M-EDI) requirements for residential buildings in the Netherlands (Brown et al. (2022), WELL v2 (2020)).

Sufficient daylight exposure

To give a proper answer to the question 'What is sufficient daylight?' we need to consider the two main functions that daylight fulfils for us. Firstly, the ability to see objects and our surroundings, by receiving photopic illuminance from daylight. Secondly, daylight allows us to have a healthy circadian rhythm by exposing ourselves to short wavelength illuminance, also known as circadian light or melanopic illuminance. Healthy threshold values can be achieved separately from one another, though fulfiling requirements for both can be a challenge.

Lighting requirements for indoor workplaces
Specific for the European context with a focus on indoor workplaces, the European norm EN 12464-1 (2021) proscribes a recommendation for illuminance levels based on the activity and type of work in a space. With more people working from home and humans spending more time indoors, these recommendations are becoming increasingly relevant for residences and home offices. Considering only the activities that occur often in a residence and require adequate lighting, the recommended illuminance values are listed in table 3. Each activity describes a required photopic illuminance value as well as a modified required value. The modified required illuminance value represents the illuminance that a person with (slightly) impaired vision would require, for example for the elderly (EN 12464-1, 2021).

For the listed indoor activities in table 3, an indoor illuminance level of 500 lx satisfies all recommendations. For visually impaired people, an illuminance value of 750 to 1000 lx is more suitable. Both illuminance values are in accordance with the medium and high requirement levels in the European norm EN 17037 (2018) respectively. For screen-related activities such as watching television, using your mobile phone or using a notebook, the contrast between the screen and its environment is more important. The recommended maximum ratio is 1:10. With modern displays having adaptive brightness control, this is expected to become less of a problem in the future.

Considering the Dutch climate and location, the medium and high requirements of the EN 17037 are presumably hard to achieve with daylighting alone, yet not impossible. Since the listed indoor activities from table 3 can occur on different times of the day, in different spaces, it is not straightforward that recommendations lead to direct design consequences. It is the responsibility of the architect and design team to create the circumstances that allow for these activities to happen at the right time, in the right space. However, once a residence allows for sufficient illuminance levels to be achieved, the tenant or owner take up the responsibility to use their indoor space as they wish.

Evidently, providing all illuminance with daylight is preferred from an energy-consumption point of view but can result in unwanted heating loads or glare issues in other moments. For some indoor activities that occur in a residence we can assume that artificial lighting is an energy efficient method to provide the illuminance that daylighting alone cannot, without losing building performance. For example, the illuminance on a kitchen countertop can be much more effectively achieved with artificial under-cabinet lighting than with daylighting apertures, especially later in the day or later in the year. It is therefore probable that designing for an incidentally occurring illuminance level of 750 – 1000 lx is not the best strategy to adopt. However, reducing the gap between illuminance due to daylight and the required illuminance for an activity is something to consider.

The EN 12464-1 not only mentions a recommended illuminance requirement but also considers the requirement for people that have an eye defect, are of older age or have an impairment. The general recommendation in those cases is that they need one 'tier' of extra daylighting to compensate their loss of sight. If a residence is designed to be inhabited by elderly people or a visual impaired person, it is recommended that the daylighting provision is one tier higher in performance. The same could be applied for residences that can (partially) fulfil a healthcare function, for example in lifetime-compatible housing. Research has to be performed if this is a realistic daylighting requirement for the Dutch urban context, also regarding other aspects such as overheating issues, glare and (unwanted) non-visual stimulus of the human body.

Recommended photopic illuminance level
In the overview of photopic daylighting requirements, for green labels and building codes it seems the strictest requirement is DF = 2.0 for 80% of a space (BREEAM-NL, 2014) and the lowest requirement is the one of 115 lx for at minimum 27.5% of a space (BBL, 2024), based on earlier findings by Bournas (2020) and Sepulveda et al. (2022). The WELL requirement positions itself somewhere in the middle, with a lower minimum area requirement of 30% but a higher minimum illuminance value (200 lx) than the BBL 2024. Depending on the simulation results, this research will conclude if static or dynamic simulation leads to more favourable results but Bournas (2020) had find CBDM simulation to be significantly more favourable in northern climates.

In any case, with photopic illuminance levels of 300 lx (DF = 2.1 in Dutch context) all requirements for building codes and green certificates are fulfiled, depending on the area that is compliant with this illuminance level (ranging from 27.5-80%). Considering the EN 12464-1's recommendations for lighting requirements for indoor workplaces, an illuminance level of 300 lx is insufficient for most tasks and additional artificial lighting is required. However, it is unknown if a higher illuminance level can be realistically achieved, not to mention if it is viable with regards to costs, facade design and building performance.

Recommended melanopic illuminance level

In the discussion of the experts led by Brown in 2020, they note that the threshold of 250 M-EDI$_{D65}$ is often not met in indoor environments even though photopic illuminance recommendations are met. This can happen in situations when overall daylight performance is insufficient, sun shading devices are in use or SPD properties of artificial lighting are unfavourable. Especially in urban context and in the scope of this research, sun shading devices and overheating are less of a concern: therefore ensuring sufficient overall daylight performance is the main problem to undertake. Simulations results of this research are used to see if this statement holds true for the Dutch urban context.

Given that the WELL v2 standard is based on the paper of Brown et al. (2022), the recommendation for melanopic illuminance is a M-EDI$_{D65}$ level of 250 lx during daytime. It should be measured in the vertical plane. Other assessment methodologies such as the EN 17037 express their performance indicator in the horizontal plane. Research is necessary to see if there is a correlation between melanopic (vertical plane) performance and photopic (horizontal plane) performance. Assuming that indoor sun shading devices and blinding curtains can block melanopic illuminance in the evening, this research will solely focus on the requirement during daytime.

The optimal point of assessment is at a height of 1200 mm which is approximately the height of a seated person. In case the interior layout of a dwelling is unknown, the WELL v2 standard assesses performance in the middle of a room. In this thesis, the analysis of melanopic performance will be performed for the whole room in this study instead. However, it should be noted that sufficient melanopic exposure is only important at the location of the occupant: a higher percentage only allows for more flexibility for the occupant to receive sufficient stimulus, hence no set percentage is recommended. The non-visual stimulus should be sufficient throughout the day between 08:00 and 18:00, therefore the time recommendation is 100% (or very close to it).

	$E_{v,d,med}$ [lx]	DF_{req} [-]	I_{req} [lx]	$DF_{req,mod}$ [-]	$I_{req,mod}$ [lx]	Maximum ratio
Reading environment, library (EN 12464-1)		3,5	**500**	5,2	**750**	N/A
Office work, office (EN 12464-1)	14400	3,5	**500**	6,9	**1000**	N/A
Cooking environment, kitchen (EN 12464-1)		3,5	**500**	6,9	**1000**	N/A
Screen-related activity, LCD (NEN 3087)		N/A	N/A	N/A	N/A	1:10

table 3: Photopic illuminance requirements for different indoor activities that require adequate illuminance values. DF metrics are converted based on the median outdoor illuminance of 14400 lx. Original requirements are in bold. (EN 12646-1 (2021), NEN 3087 (2011)).

	photopic illuminance				melanopic illuminance		
	$DF_{rec, NL}$ [-]	I [lx]	area [%]	time [%]	M-EDI $_{D65}$ [lx]	area [%]	time [%]
Lawful minimum	1	144	27.5 - 50	50	N/A	N/A	N/A
EU minimum	2.1	300	50	50	N/A	N/A	N/A
Study recommendation	**2.1**	**300**	**50**	**50**	**250**	N/A	**100**

table 4: The photopic and melanopic recommendations, based on literature research. Daylight factors are calculated for Dutch context, based on a median sky illuminance of 14400 lx under overcast sky conditions. M-EDI recommendations are for all daylit hours between 08:00 and 18:00.

research methodology

Assessed urban locations

This thesis will investigate daylighting performance in different urban areas throughout the Netherlands. With the available timeframe and complexity in mind, six locations are assessed for their performance for three standardized residences. The locations all represent different urban areas that can be found throughout the Netherlands: from the post-war era to modern city centres.

Classification of Dutch urban areas

In this research, urban density is expressed using the FSI, GSI, OSR and L density indicators. These density values can be plotted on the Spacemate graph (Berghauser-Pont & Haupt, 2007) and compared to each other. The urban scale that we are most interested in is on the gross building block scale: it allows us to retrieve data in an area that fits future daylighting simulation, giving a good idea of the actual urban density of our assessed urban context.

In the original Spacemate publication (Berghauser-Pont & Haupt, 2004) the writers distinguish different grades of urbanism and plotted those values in the Spacemate. To cover most of the Dutch urban areas, our locations must cover the most relevant grades of urbanism. Except for the rural areas, the six locations in this research cover all bases. It is not expected that daylighting performance is at risk in rural areas, hence why there is no location in that category. The four grades of urbanism are plotted in Figure 10.

Extracting urban density values

To prevent picking locations at random and see if they fall in an uncovered spectrum of the Spacemate, geographic information systems (GIS) software is used to visually identify fitting urban patches for this research. QGIS (2023) is a program that allows the user to load the RUDIFUN database by the PBL (2022), which contains all the urban density values of the Netherlands. Basic filtering queries allows us to select certain density values and visually represent them inside the software, with any topographical map as an underlayment. An example of this workflow can be seen in Figure 11. Demonstrated is the output of QGIS around the area of Rotterdam central station, filtering the gross building blocks with an FSI value greater than 1.5, representing urban & highly urban densities (darker is more dense).

In the initial search for assessment locations, the study was interested in the highest urban density areas in the Netherlands. It was expected that the worst daylighting conditions are found in these type of areas. The Amsterdam Zuidas district and the Rotterdam Maritime district are both areas with one of the highest urban densities in the RUDIFUN database (2022). What makes them suitable for this research is that it is not a single gross building block that is dense: it is a collection of multiple gross building blocks that make an equally-dense urban patch. This removes any bias where one side of a building can be much less dense than the other, invalidating simulation results. This principle was then applied to all other locations, requiring multiple gross building blocks to have (somewhat) similar density values.

Based on real-life references and experiences, an FSI of 1.00 was found to be the lower limit of an 'urban area'. Almost no medium or high-rise buildings are found in areas with this density, and certainly not multiple building blocks. Therefore, in areas with an FSI lower than 1.0, no daylighting issues are expected, hence they are not represented in this study.

An area that has a relatively low urban density but does have tall buildings is the Delft Voorhof district. In this research, Delft represents the lowest urban density. As a control, another area with a similar FSI is selected which would be a selection of building blocks in Rotterdam North. With a higher GSI value, meaning the buildings blocks are more compact, Rotterdam North represents a density that is commonly found in the bigger cities of the Netherlands.

Ideally, other locations fill the gap between the highest urban densities (Amsterdam, Rotterdam Maritime) and the lower urban densities (Delft, Rotterdam North). Using filtering queries in QGIS, an urban patch in Eindhoven was suitable for this study, sharing GSI properties with Rotterdam North and Amsterdam while having an FSI value that is in between both. A location with a similar FSI to Eindhoven is the old city centre of Utrecht, introducing a completely different urban setting to this research.

After six suitable locations were identified, a building block was chosen and replaced with a standard residential building to assess its daylighting performance. The building plot should be multi-oriented, a realistic situation and needs to fit the size of the standardized building. The final locations are shown in Figure 12.

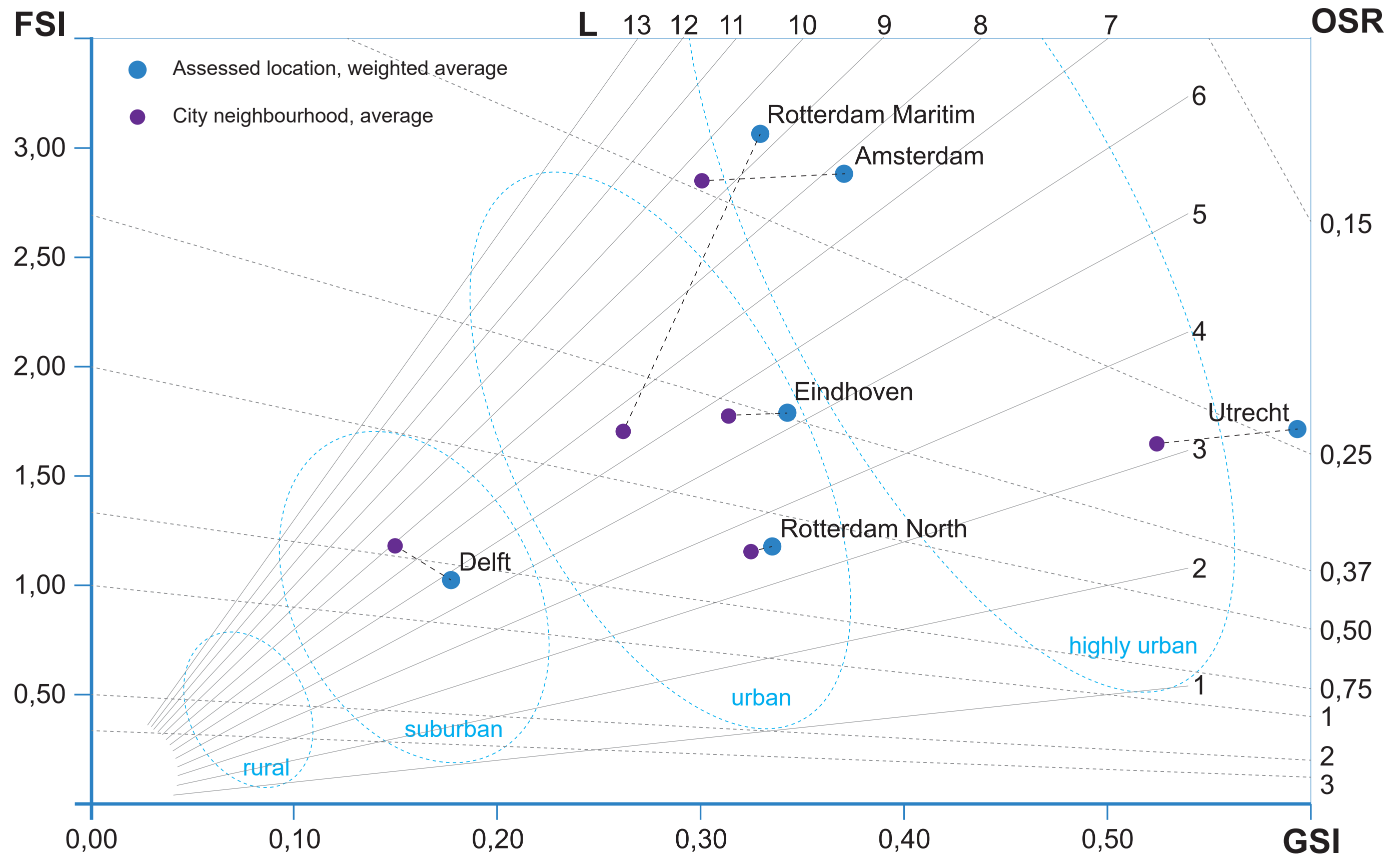


Figure 10: The Spacemate graph with the assessed locations and the grade of urbanism according to Berghauser-Pont & Haupt (2004). On the Y-axis is the FSI and OSR value, on the X-axis the GSI and L values. Blue dots represent the weighted average density of the urban patches, purple dots represent the gross neighbourhood average. Redrawn by the author. (Original: Berghauser-Pont & Haupt, 2004).

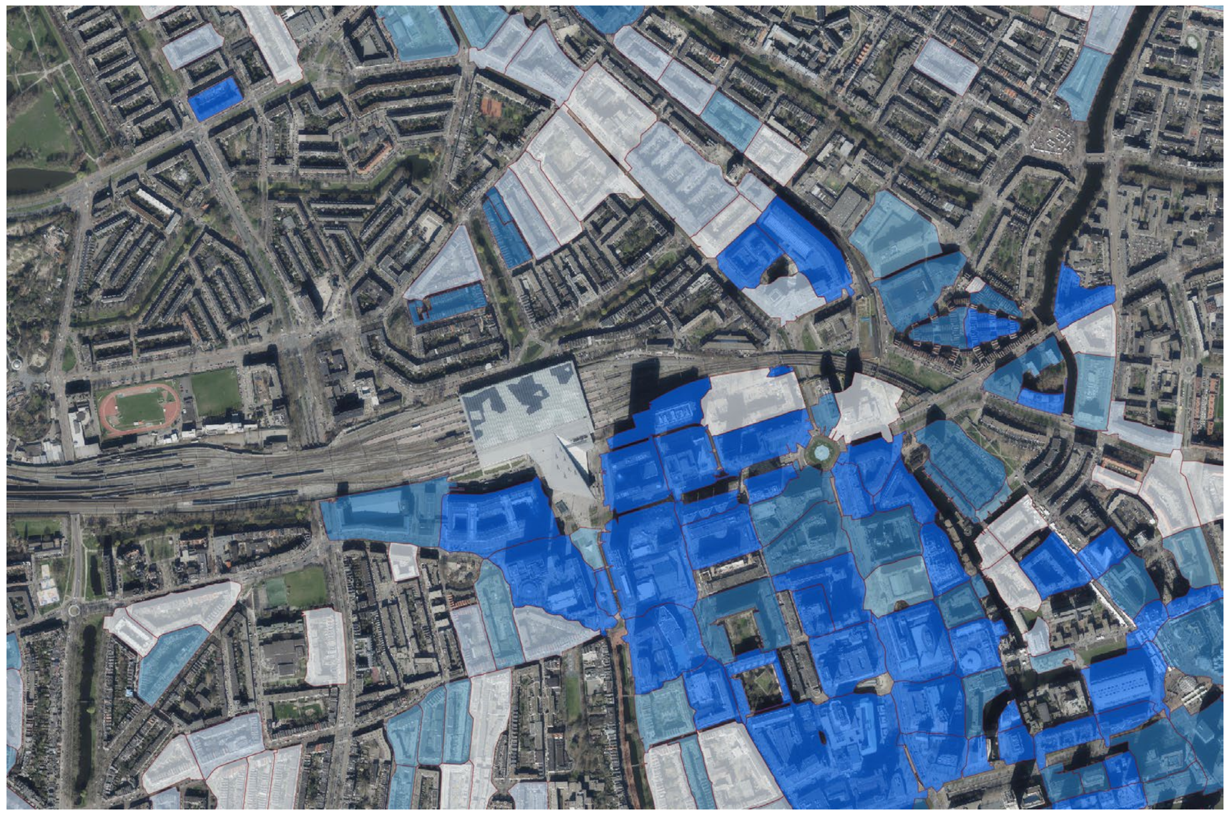


Figure 11: An example output of QGIS using the RUDIFUN database (PBL, 2022) with aerial photographs as a base layer. Visible are only gross building blocks with FSI ≥ 1.5. The gradient is for Figure purposes only. (own source).

Density and reflectance characteristics
In order to understand the impact of urban context on daylighting performance, realistic 3D geometry and reflectance values need to be implemented in the simulation model. Once the model is simulated, combining the output with different parameters allows us to assess the effect of urban density on daylighting performance.

First, for all six locations, the urban density values are calculated. Suitable locations were found using QGIS and all locations have multiple building blocks with similar density values. To come to the plotted density values in Figure 10, the weighted average density from all adjacent gross building blocks is calculated. These are plotted in blue. All building blocks that have been included in this calculation can be found in Appendix 1 for all locations. The density data is derived from the RUDIFUN database (PBL, 2022).

As a control, to see if the location's density is representative for its neighbourhood, the density values of the gross neighbourhood are also plotted in Figure 10. This data also originates from the RUDIFUN database (PBL, 2022). For all locations, the gross neighbourhood density is close to the weighted average density of the assessment locations, meaning that the locations are representative for larger urban patches. The exception is the Rotterdam Maritime patch: the gross neighbourhood includes large bodies of water because of the river Maas that is close by. This increases the total "ground" surface area without any buildings, decreasing the density significantly. With this in mind, it is expected that the weighted average density comes close to the rest of the neighbourhood.

Secondly, the reflectance properties of each urban location are derived and calculated. Using the data from the example residences by the RVO (2022), average window-to-wall ratios (WWR) are calculated for each residential type, for each time period. This results in a realistic (weighted) reflectance value for every residential building within the urban patch of interest, based on openly available data provided by the RVO. The calculated reflectance values using this method have small variations, hence it is expected that no large differences due to reflectance values are expected in the simulations. An overview of the reflectance values of all adjacent building blocks is presented in Appendix 2.

The building reflectance properties will be assigned to the corresponding 3D geometry in the simulation model. The geometry of the urban context is mesh geometry from openly available databases, published by TUDelft3D (2023) in an online environment (Nederlandin3D.nl). The geometry data is a combination of point cloud data from AHN National Height Model of the Netherlands (AHN, 2019) and BAG Register of Addresses and Buildings (BAG, 2022) to create 3D geometry. Level of Detail (LoD) 2 is used in the exports for this thesis. No building geometry is post-processed by hand to recreate the workflow of an architect or consultant. Missing buildings are included by manually drawing them in Rhino.

Thirdly, existing green patches and water bodies are included in the simulation models. Although in cities the ground surface area is typically hardened and dark of color, patches of grass and water bodies can significantly impact the average ground reflectance. To include these surfaces in the simulation models, the projection of greenery and water is imported from the BGT database (Basisregistratie Grootschalige Topografie; the Netherlands central registration of large-scale topography, 2022). This database is used by government agencies and contains detailed information on all landscape elements in the Netherlands i.g. trees, street lighting and more. In this thesis, layers *Water area, Unclassified water area* and *Overgrown area* are used to import all relevant patches in the model. Elements of temporary nature are not included in the model (e.g. trees and bushes).

To simplify the model geometry and to prevent possible errors, all geometry (buildings and ground faces) is flattened on the world plane. Therefore, no height differences are included in terrain or building patches. For the Netherlands, it is expected this will not affect the results much but it should be noted that this can be more important in other locations.

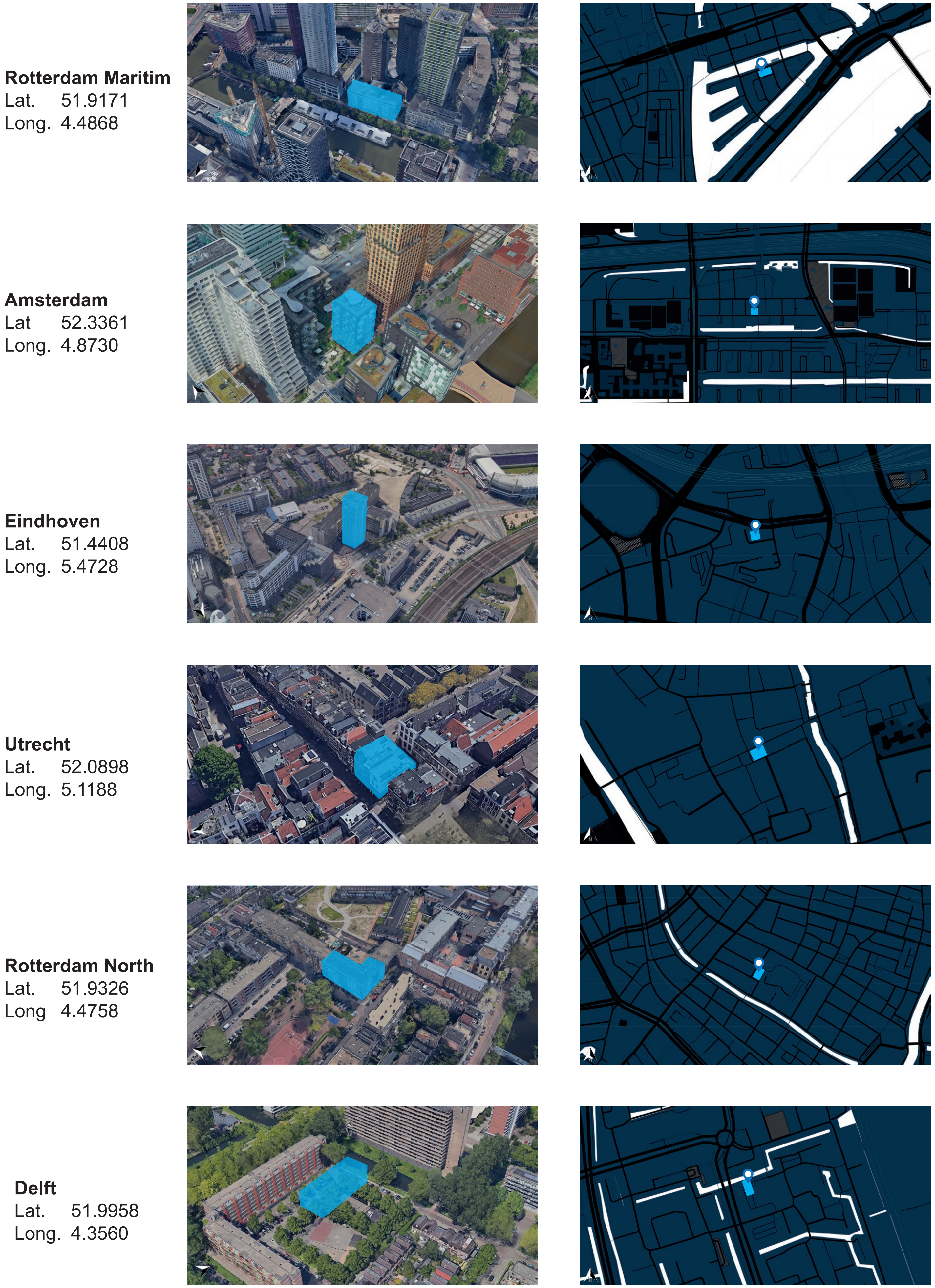


Figure 12: The six assessed locations in this study with coordinates. In white are water bodies, in black is the main road network. Illustrations not to scale. (Google Maps, 2023).

Correct data on material reflection is crucial for realistic reflectance values in the built environment. For this study, opaque material data is gathered from SpectralDB (2023). SpectralDB is a material reflectance database, maintained by J. Alstan Jakubiec (University of Toronto). It contains detailed reflectance properties of various materials, which is necessary to get valid results in photopic daylight simulation as well as in melanopic daylight simulation. In table 5 are all exterior materials shown, as well as the ID number of the material in the SpectralDB database.

It is assumed that the predominant facade material is masonry with a 'dark' color (red/brown/grey), especially in older Dutch buildings. Hence this research adopts this as the material for all residential buildings. In situations where it is assumed that this assumption would diverge the results (i.e. office buildings and parking garages) it is assumed that a different material is used. For offices, standard metal cladding is used as the predominant material and for parking garages, the 'transparent' surface area has a reflectance of 0%.

For context reflectance values, greenery and water reflectance properties are based on studies by Chiodetti et al. (2018) and Srivastava (n.d.). In the simulation model, all hardened surfaces such as roads and pavements are merged and are assigned the same reflectance value of asphalt and concrete tiles. Over time, the reflectance properties of these materials decline due to an increase in the roughness of a material. This effect is not included in this thesis.

For the glazing surfaces, the exterior reflectance properties originate from WINDOW software, a program published by LBNL (n.d.). The properties originate from the standard built-in window properties for e.g. clear single glazing. For the weighted average reflectance of the buildings, the most probable glazing system is chosen for each building. The decrease of reflectance due to dirt on the glass surfaces is not included in this thesis.

This thesis is interested to see if the reflectance values and the assumption of materialisation swing the simulation results in one way or another. Therefore, a sensitivity test on building reflectance and ground reflectance has been performed for Amsterdam context. The results of the sensitivity analysis are further discussed on pages 49-50.

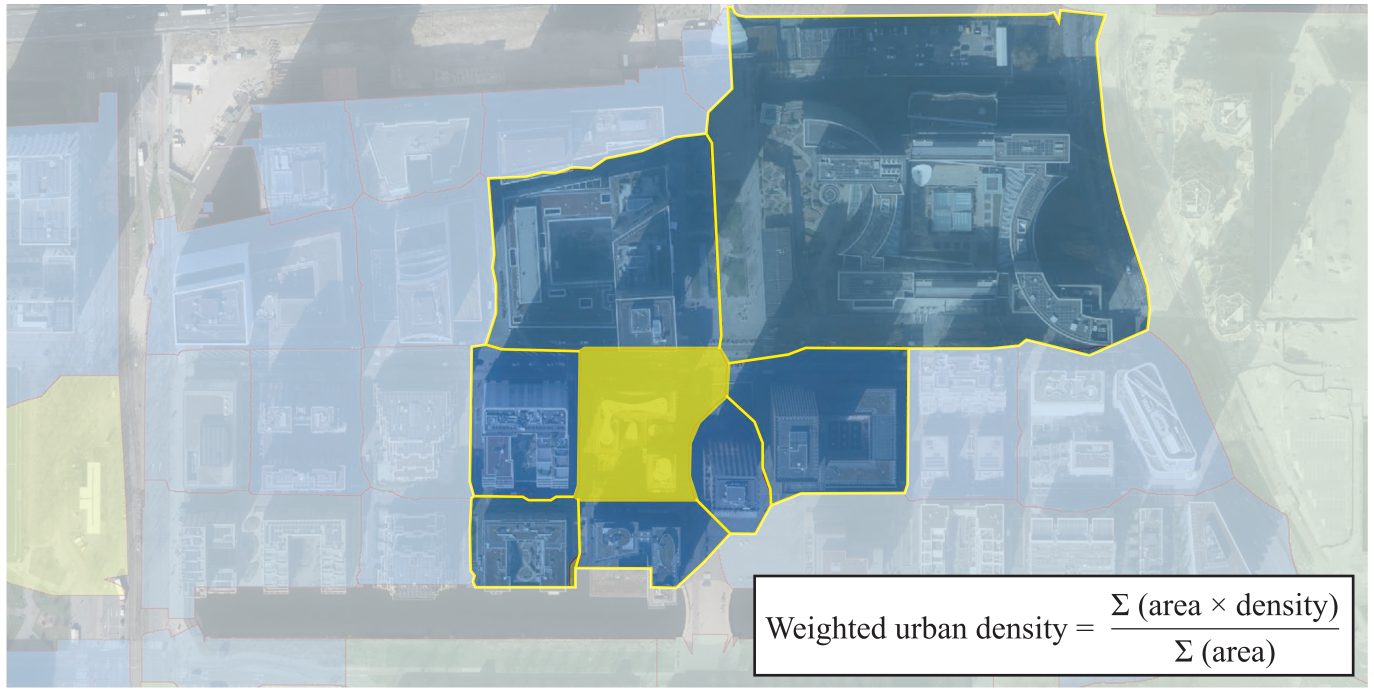


Figure 13: An example on the calculation of the weighted urban density. In yellow is the gross building block of the standard residential building, in yellow encircled are all adjacent building blocks that are included in the calculation. Data from RUDIFUN (PBL, 2022). Own source.

parameter	*material, specification*	*reflectance value*		*transmission value*		*source*
		V(λ)	*M(λ)*	*V(λ)*	*M(λ)*	
context masonry	brick, red	13.8	9.0	N/A	N/A	SpectralDB (00115)
context cladding (office)	aluminium, grey	20.0	18.9	N/A	N/A	SpectralDB (00027)
context glass	clear single, 6mm	8.2	N/A	N/A	N/A	WINDOW 7.8
context glass	clear double, 12mm	14.4	N/A	N/A	N/A	WINDOW 7.8
context glass	double low-E, 12mm	12.0	N/A	N/A	N/A	WINDOW 7.8
context road	Asphalt / concrete tiles, worn	18.0	13.8	N/A	N/A	SpectralDB (01100)
context greenery	grass, normal	25.0	16.2	N/A	N/A	Chiodetti et al. (2016)
context water	water, normal	10.0	6.5	N/A	N/A	Srivastava (s.d.)

table 5: Material reflectance and transmission properties for the urban context buildings. Opaque material properties are retrieved from SpectralDB (2022) including their ID number. Glazing materials are from WINDOW 7.8 by LBNL (n.d.). Values for greenery and water come from Chiodetti et al. (2016) and Srivastava (n.d.). Own Source.

Assessed residential buildings

Different urban situations ask for different building typologies to be assessed. To accommodate this, two standard building designs are assessed for their daylighting performance. One building is a residential tower, typically found in higher density areas, and the other building is a walk-up apartment building which is typically found in medium-density areas. The tower will be assessed in the context of Amsterdam, Rotterdam Maritime and Eindhoven. The walk-up apartment building will be assessed in the context of Delft, Utrecht and Rotterdam North.

In this study, the designs do not consider any ventilation requirements or other design features in the windows such as sun shading. This is not the focus of this research since it is focussed on providing sufficient daylight, not on reducing solar heat gain or reducing glare. For the loggia window frame, no operable door is simulated for the same reasons.

High-density: tower building
The residential tower's floor plan is shown in Figure 14. The tower consists of eight residences: four double-oriented residences (Type A) and four single-oriented residences (Type B). The residences are connected through a single core of which the design is compliant to the Building Code 2012. Both housing types are provided with a loggia, one bedroom, one living room/kitchen area and sufficient space for a bathroom, storage space, and mechanical equipment. In total, the tower consists of 23 floors of 3 meters height, for a total height of 69 meters: just under the 70 meter above which a building needs to fulfil extra requirements for fire safety.

The tower's configuration allows for comparison between different orientations, which is especially useful when assessing performance in a dynamic simulation where orientation is of significant influence on the performance. As for the static simulation, orientation does not influence the DF metrics but can be used to gather more data on possible performance indicators such as the sky view factor (SVF).

Medium-density: walk-up apartment
The configuration of the walk-up apartment building is similar to the tower's configuration but it is smaller in size and therefore fits more appropriate in medium-density areas. A part of the floor plan is shown in Figure 15. The building consists of type A residences on the corners and type C residences for other spots. The single-oriented residence type C does not have a loggia but instead has a larger living room/kitchen area. Type C's residence design is also compliant to the Building Code 2012. The entrance to the apartments is via a central core in the middle of the building, as can be typically found in Dutch walk-up apartment buildings.

The building configuration is smaller in size, making it possible to assess performance in narrower streets without it being unrealistic. Residence type C does not have a loggia because Building Code 2012 allows shared outdoor space for residences under 50 m^2, for example on the roof.

Condensing results: simplified buildings
Recording the performance of two daylit rooms per residence complicates the simulation script and the output of results into Excel or SPSS. To simplify the process and data analysis, the residences are simplified by creating one open space per residence without interior walls. The loggia remains identical, and facade properties are kept similar.

First, it is important to understand the performance difference between this 'standard' and 'simplified' layout as it is called in this study. Therefore, a comparison has been done for all three residential types. The use of this comparison is to understand how the results are influenced by interior layout, rather than other aspects such as urban density. The results of this comparison can be found on pages 34-35. The assessed layouts can be seen in Figure 16 and 17.

In further simulation with urban context, the simplified interior layout will be used. For consistency, all facade characteristics such as WWR and glazing height is kept as identical as possible. However, the position of the windows has changed slightly to achieve equal spacing between windows. The differences between the standard and simplified layout are listed in table 6.

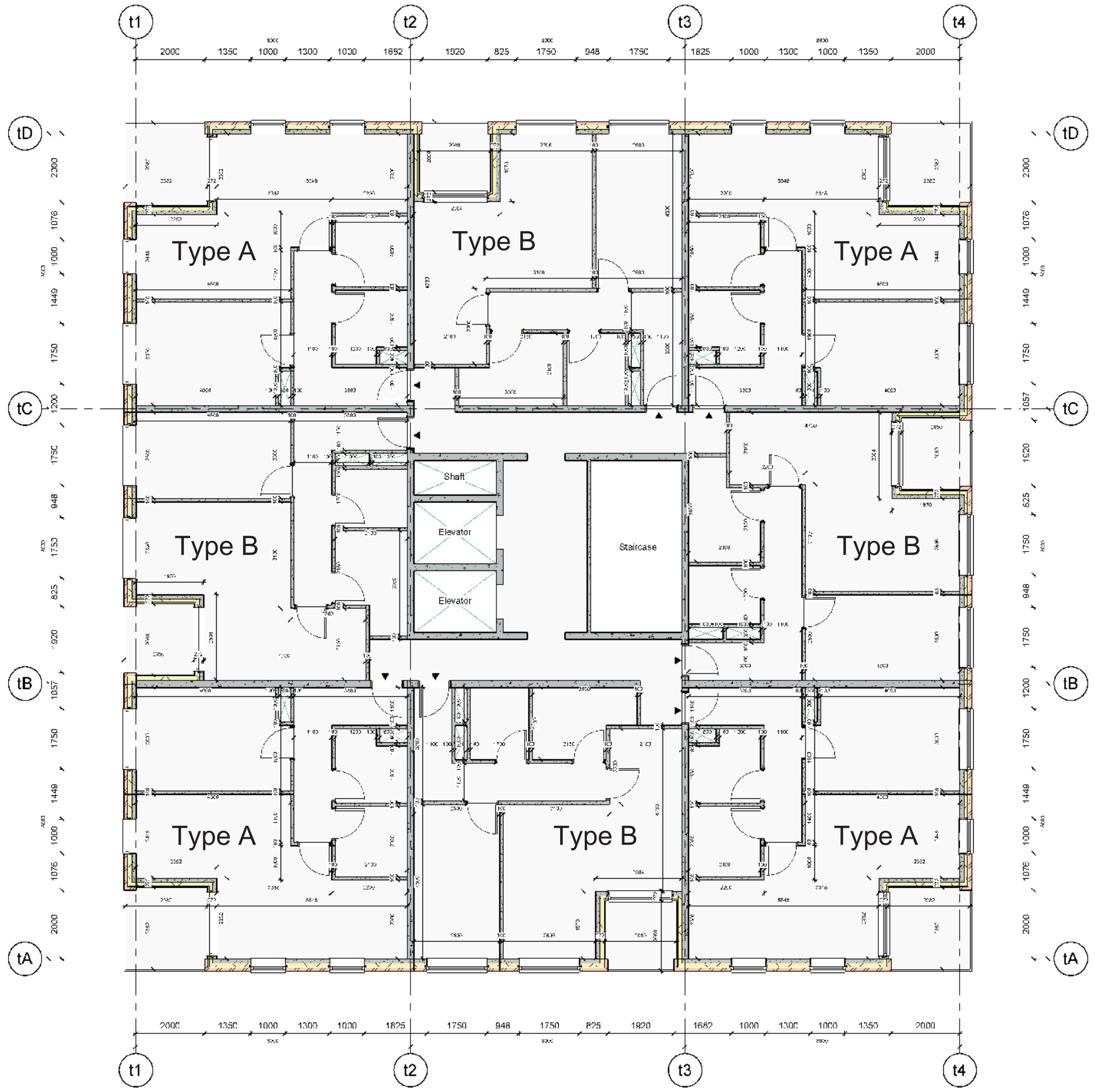


Figure 14: floor plan of the assessed residential tower, showing two housing types A and B. Dimensions in mm. A larger size of the floor plan is in appendix 3. Own source.

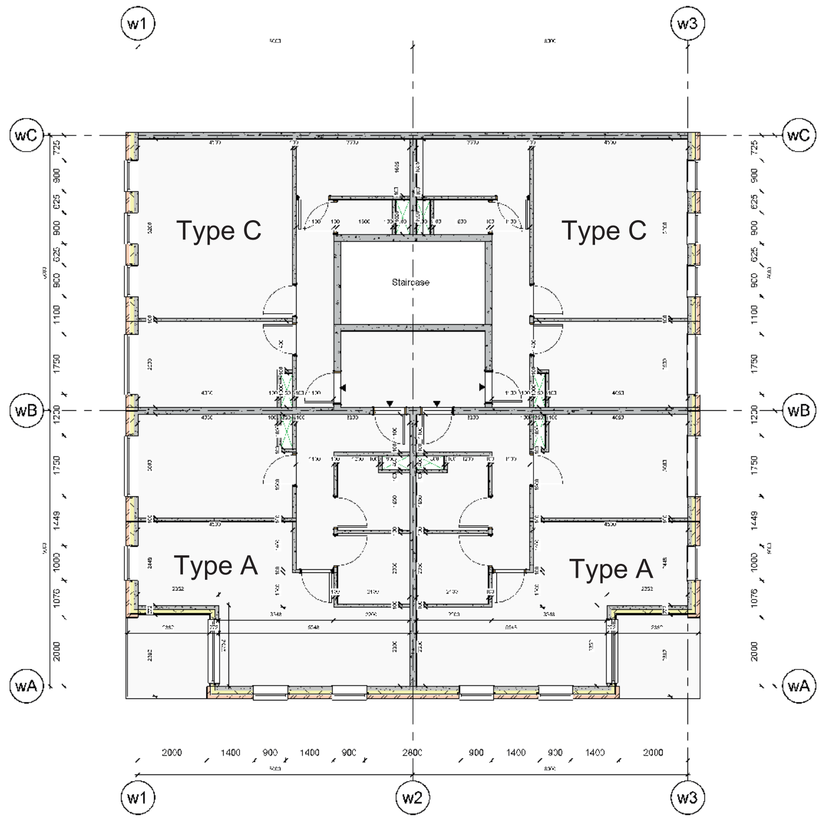
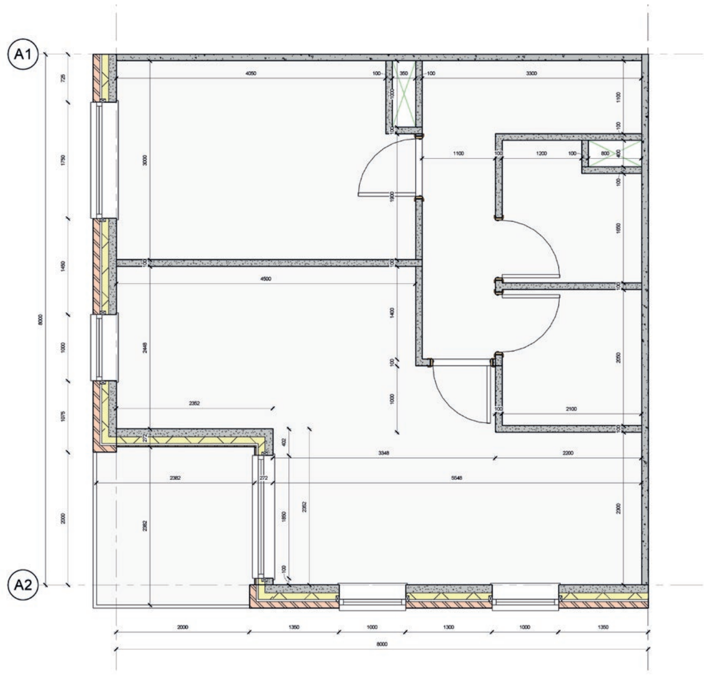


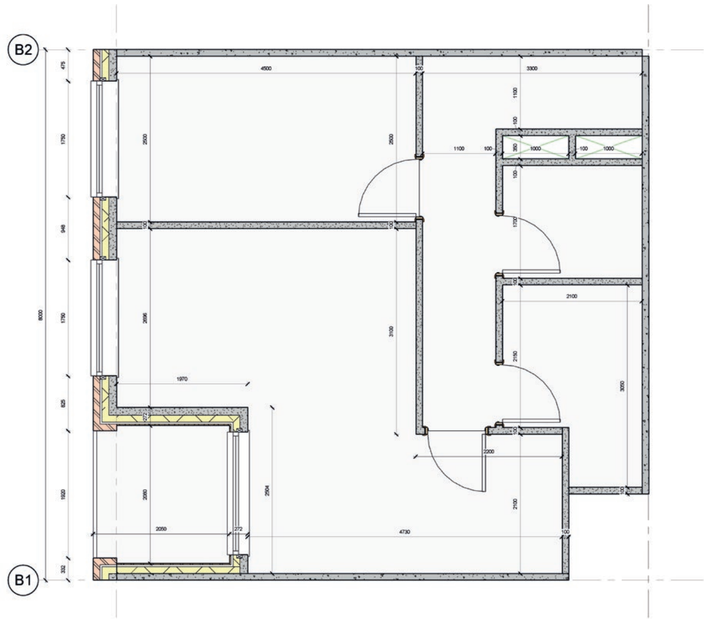
Figure 15: floor plan of the assessed walk-up apartment building, showing two housing types A and C. Dimensions in mm. A larger size of the floor plan is in appendix 4. Own source.

Figure 16abc: floor plan of the residences A, B and C with standard layout. Dimensions in mm. Own source.

Type A - standard layout
1 bedroom
1 kitchen/living room
corner loggia



Type B - standard layout
1 bedroom
1 kitchen/living room
loggia



Type C - standard layout
1 bedroom
1 kitchen/living room
no loggia (< 50m²)

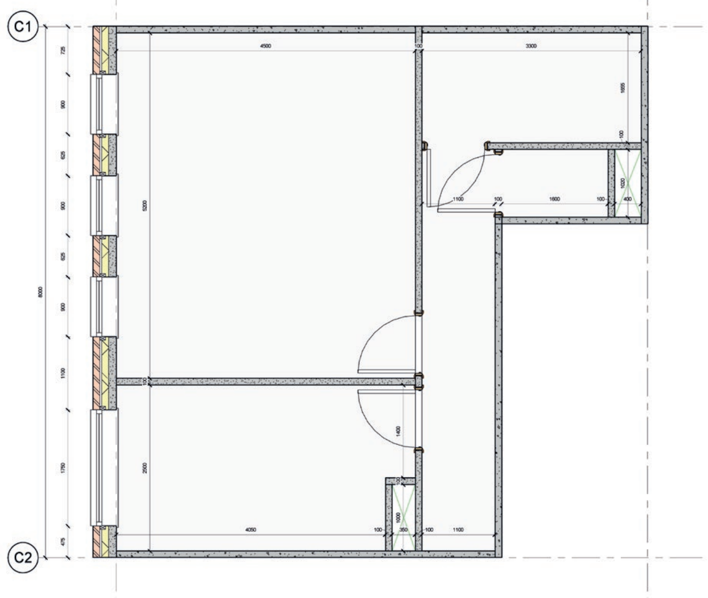
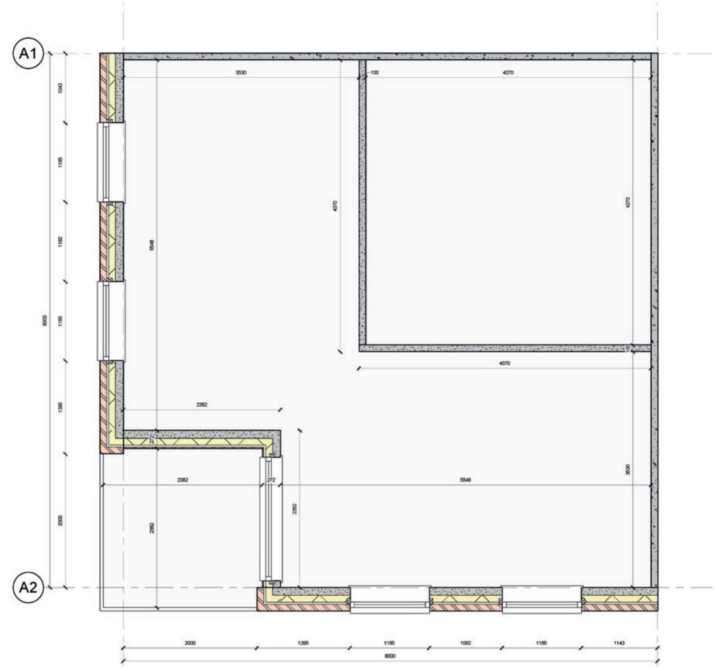
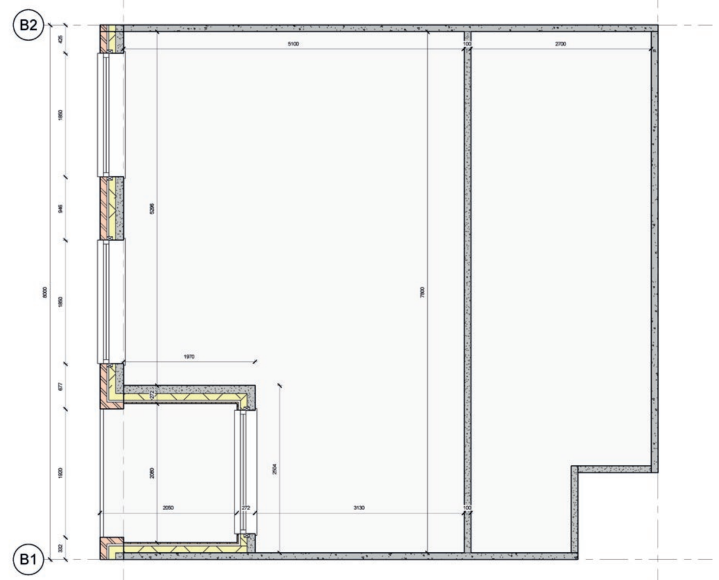


Figure 17abc: floor plan of the residences A, B and C with simplified layout. Dimensions in mm. Own source.

Type A - simplified layout
1 occupied space
corner loggia
equally spaced windows



Type B - simplified layout
1 occupied space
loggia
equally spaced windows



Type C - simplified layout
1 occupied space
no loggia (< 50m²)
equally spaced windows

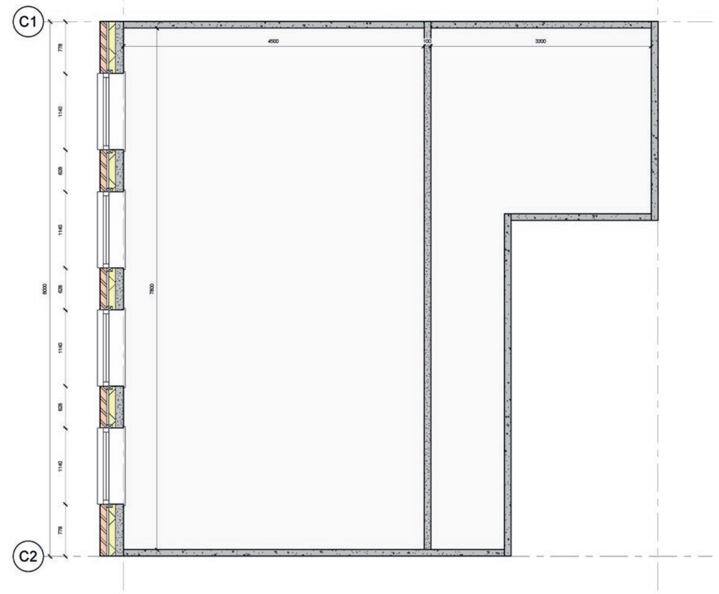
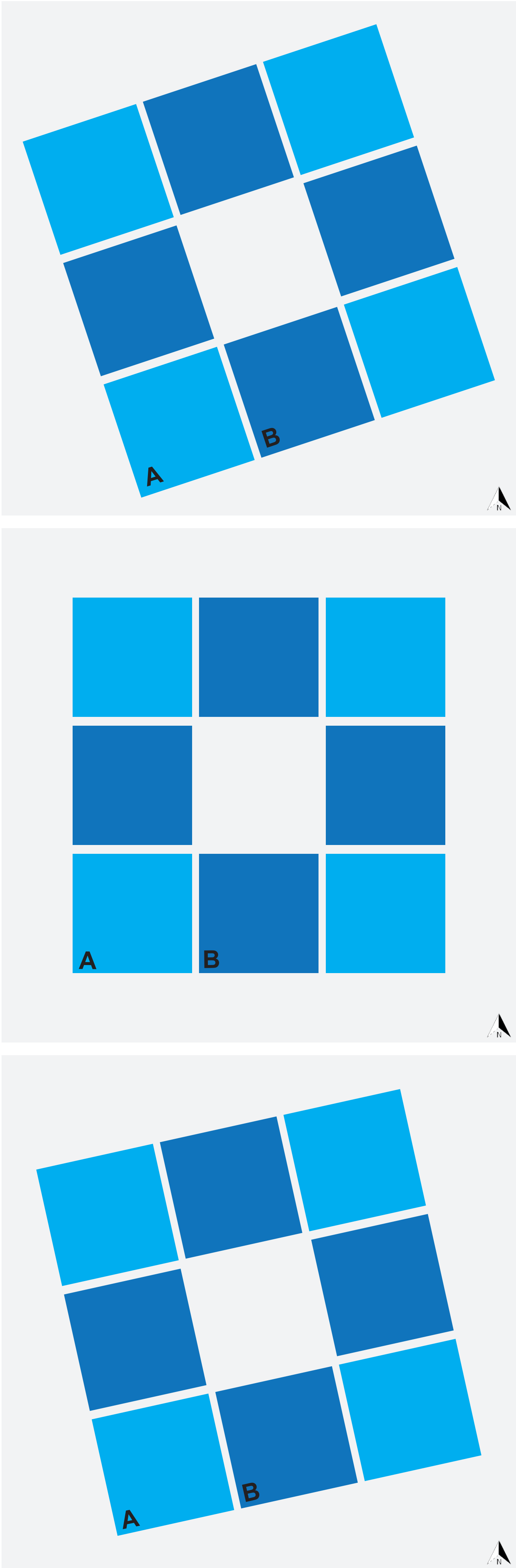


Figure 18: schematic floor plan of the residential types in urban context. Illustration is not to scale. Own source.

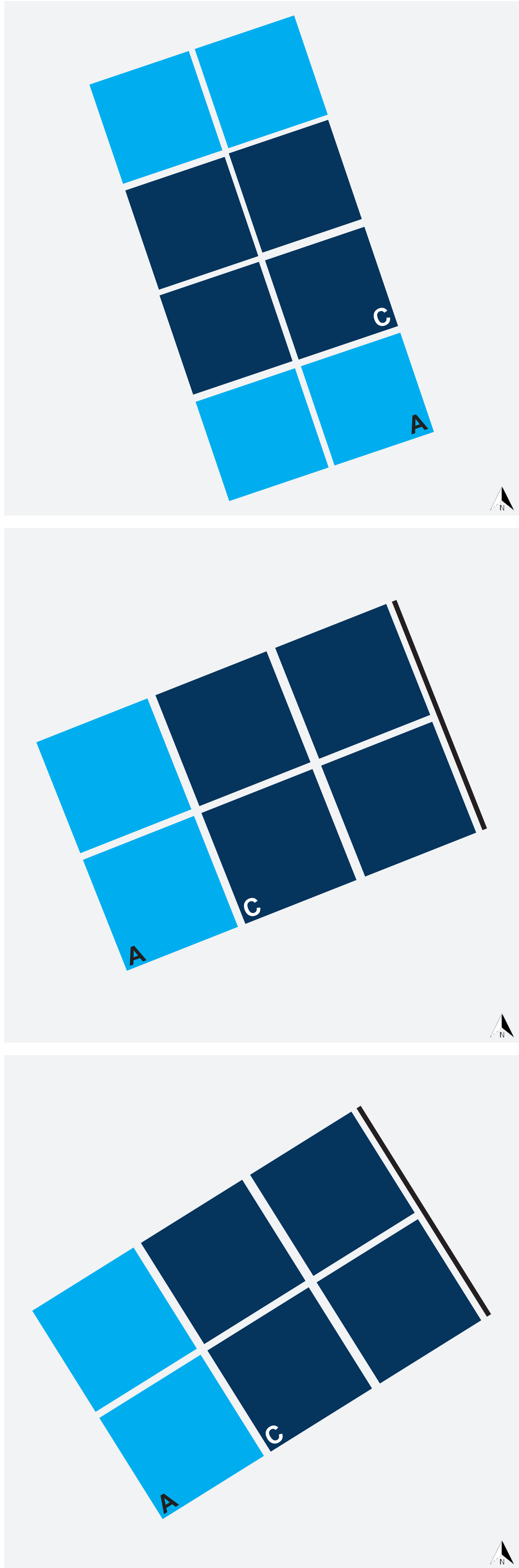


Rotterdam Maritime
18.4°
4x type A
4x type B

Amsterdam
0.0°
4x type A
4x type B

Eindhoven
12.5°
4x type A
4x type B

Figure 19: schematic floor plan of the residential types in urban context. The black line is an adjacent building. Illustration is not to scale. Own source.



Delft
18.7°
4x type A
4x type C

Utrecht
21.6°
1x type A
4x type C

Rotterdam North
32.0°
2x type A
4x type C

Transmission & reflectance properties
Radiance and LARK require detailed material properties to be set to achieve reliable results. The overview of all material properties of both the standard and simplified residences are shown in table 8. For daylighting simulation, only finished face properties are of importance, so other construction materialisation is undecided on.

Most important is that all properties remain identical throughout the photopic and melanopic simulations. Only the reflectance properties of the urban context are varying per location. For interior materials, standard finish materials are used i.e. light wooden laminate flooring and white painted ceilings. The spectral properties are close to the standard reflectance values as specified by the design guideline NPR 4057 (2022) within 15%. All spectral information is collected from SpectralDB (2023).

The transmission values for the fenestration system are calculated using Berkeley lab's WINDOW 7.8 software (LBNL, n.d.). WINDOW 7.8 can be used to create custom glazing systems and to calculate accurate transmission rates for different wavelengths. WINDOW 7.8 uses glazing data from the international glazing database (IGDB, 2023). The IGDB is maintained and published by the Lawrence Berkeley National Laboratory (LBNL, n.d.).

For the reflectance properties of the urban context, the standard glazing systems of WINDOW 7.8 are used in the calculations. For the assessed residences, only the transmission values are used in daylighting simulation. The glazing used in the residences is a triple glazing system by Pilkington (2023) in a 6*-12-4*-12-4 configuration with transparent coating on positions 1 and 4 (unless specified otherwise). The layers in the glazing system can be found in table 7 and its optical properties are calculated with WINDOW 7.8.

residence	variation	daylit floor area [m2]	interior ceiling height [mm]	average WWR [-]	total window area [m2]	interior window depth [mm]
Type A	standard	38.09	2750	0.350	15.38	222
	simplified	38.65	2750	0.326	15.35	222
Type B	standard	34.34	2750	0.600	13.21	222
	simplified	34.85	2750	0.600	13.21	222
Type C	standard	34.16	2750	0.481	10.58	222
	simplified	34.87	2750	0.482	10.61	222

table 6: Description of the image. Dimensions or units in mm or whatever. Own source. (External source, 2023).

layer	IGDB ID	manufacturer	specification	thickness	reflectance value		transmission value	
					V(λ)	M(λ)	V(λ)	M(λ)
1	4157	Pilkington	Suncool 50/25	6*				
2	9	N/A	argon 90%	12				
3	16682	Pilkington	Optitherm s3	4*				
4	9	N/A	argon 90%	12				
5	4116	Pilkington	Optifloat clear	4				
				Total	19.3	N/A	42.8	N/A

table 7: Optical properties of the triple glazing system as used in the simulation for different residential types (Pilkington, 2023; IGDB, 2023; LBNL, n.d.).

parameter	material, specification	reflectance value		transmission value		source
		V(λ)	M(λ)	V(λ)	M(λ)	
flooring	laminated, maple	35.9	25.7	N/A	N/A	SpectralDB (00434)
ceiling	painted, white	88.4	87.5	N/A	N/A	SpectralDB (00583)
Interior walls	plaster, beige	63.0	54.4	N/A	N/A	SpectralDB (00704)
loggia flooring	concrete, light gray	34.6	29.7	N/A	N/A	SpectralDB (01074)
loggia ceiling	fire-retarding panels, offwhite	82.9	81.3	N/A	N/A	SpectralDB (01286)
loggia walls	wooden slats, untreated	31.9	19.0	N/A	N/A	SpectralDB (00092)
loggia fence	barred metal, 90% open	10.4	9.2	N/A	N/A	SpectralDB (00670)
Windows	mullion, aluminium, matte gray	43.3	42.7	N/A	N/A	SpectralDB (01091)
	standard aperture, triple glazed	19.3	?	42.8	?	WINDOW 7.8

table 8: Material properties for all used finish materials in the model (SpectralDB, n.d.; Pilkington, 2023; IGDB, 2023; LBNL, n.d.).

Simulation setup

Both photopic and melanopic simulation were performed to assess daylighting performance. Literature research has led to the conclusion that for a complete overview of performance, both static and dynamic simulations need to be run. Static simulation can be used for comparison to the EN 17037, BBL and to test worst-case conditions. Dynamic simulation is expected to be better for assessing the impact of urban context and considers climate data. Melanopic simulation is assessed as a static point-in-time simulation for a limited number of days.

Software & programs
The illuminance values will be simulated using the Radiance engine inside the Honeybee plug-in for Rhinoceros 7. Radiance has proven to be reliable and accurate for academic research (Mardaljevic, 1995). The simulations were executed faster with the use of Accelerad software. This allows Radiance to make parallel calculations using the graphical processing unit (GPU) of a computer, significantly reducing simulation time with only a small trade-off in accuracy if no complex fenestration systems are modelled (Jones & Reinhart, 2015; 2017; Jones, 2020). Accelerad showed artifacting issues in fish-eye rendering but for daylight factor and daylight autonomy simulation, the results were verified with a control run using regular Radiance. Honeybee and Grasshopper are used to input Radiance parameters and 3D geometry. This allows for flexibility and quick adjustments if necessary. The used Radiance simulation parameters are shown in the table 9 for both static and dynamic simulation.

Melanopic simulation is also done with the Radiance engine but it is initiated by the LARK plugin. LARK (2022) for Grasshopper is a plugin that runs Radiance for nine channels separately, enabling us to calculate the spectral irradiance for specific parts of the light spectrum. The plugin has been developed by Inanici (University of Washington) and ZGF architects. After the beta launch in early 2019, others joined developing LARK. Among the supported output metrics, it supports output directly in M-EDI_{D65} which is the most important metric for non-visual light assessment in this thesis. LARK is easily integrated with Honeybee models which are already used for the photopic simulation, making LARK a good fit for this study.

Geometry and simulation settings
The urban context and ground surfaces need to be modelled and inserted into the Honeybee Radiance model. To model the urban context for the daylighting simulation, openly available BAG (2023) and PDOK (2023) data is used. It is important that the data contains the correct shape and height of buildings since this is of influence on daylighting performance and different indicators. All buildings that touch on a radius of 150 meters will be considered in the daylighting assessment. This corresponds roughly with the urban patch size of which the urban density values are calculated. With some exceptions, this range is sufficient to consider all adjacent buildings but also taller buildings that might obstruct sky view and could affect performance.

The residences are drawn according to the floor plans of Figures 16 and 17 (also found in Appendix 3 and 4) in Rhinoceros 7. Only the outer faces that reflect any irradiance are drawn; other faces are left out to simplify the model. Other parts of the residential building, such as the floors above and under the floor-in-question are modelled as boxes to ensure they cast shadows on surrounding buildings, ensuring realistic simulation output. For the reflectance value of the assessed building, an estimated reflectance is taken for a flat building built in 2015-2018 (RVO, 2022).

In order for the simulation to be run, sensor points need to be defined. This could either be a singular point in space (placed by hand) or a sensor grid. A sensor grid is required to assess performance according to EN 17037. The sensor grid is defined as equally spaced points across all the occupied spaces. The points are offset 500mm from all walls, and a distance of 200mm is in between all points. This results in a large number of sensor points, ranging from 568 (type A, simplified) to 620 (type C, simplified). The number of points is used to convert Cumulative Annual Irradiance [W m^{-2}] to Total Annual Illuminance per sensor point (TAI [klxh]). The distance from the sensor points to the floor is 850mm which is in line with the EN 17037. The clear ceiling height is 2700mm and the residential tower has a total of 23 floors. The walk-up apartment has only 5 floors simulated, which is more realistic in the urban density that can be found in those areas.

The Radiance parameters are initially repeated from other studies and later adjusted in a convergence test. Single parameters values were increased until no significant change was occurring anymore (+/-5%). The adjusted parameters are presented in table 9. Other parameters are copied from the built-in 'Radiance Parameter' component inside Honeybee. Rerunning simulation with similar parameters usually do not differ in outcome for more than 2%, which is considered sufficient for this study.

Photopic illuminance simulation
For photopic daylighting performance, the residences will be analysed for their compliance to the minimum daylighting requirement of the thesis. The requirement of this study is set on an illuminance value of 300lx which can be translated to a daylight factor (DF) of 2.1 for Dutch context. This is in line with the minimum requirement according to the EN 17037 norm (2018) but well above the requirement for the BBL (2022). Therefore, the output metric for static simulation is the DF percentage that fulfils the requirement (DF ≥ 2.1).

In the dynamic simulation, daylight autonomy will be analysed over a time period of a year. The requirement is 300lx and this needs to be fulfiled for 50% of the daylight hours in a year. This leads to a requirement of $DA_{300,50\%}$. Since the DA performance of a residence cannot exceed 100% (making it unsuitable for statistical analysis), another metric is introduced with continuous values which allows for a normalisation of results between different residential types and orientations. The total annual illuminance (TAI) will be simulated for each point on the sensor grid. Addition of all values and dividing them by the sensor count gives an average TAI value per sensor point, resulting in the TAI metric in klxh.

Static simulation will be run under standard CIE overcast sky conditions with a mean global illuminance of 14400 photopic lx, compliant with EN 17037. Only the reflectance values of materials do not align with the requirements in the Dutch NPR 4057 (2022) but do fall within the boundaries of the EN 17037 (2018). The simulation is compliant with all other relevant requirements from the NPR 4057.

Dynamic simulation will be run with the climate data of location 'Amsterdam Schiphol airport' (52.3095, 4.7630). As mentioned in the boundary conditions, climate differences are small in the Netherlands, so no discrepancies are expected. The simulation will be run for all daylit hours to assess the annual performance metrics. These hours are filtered within Grasshopper using Ladybug components. The results are compared to threshold performances determined by literature research.

ambient accuracy	*ambient bounces*	*ambient divisions*	*ambient resolution*	*ambient super-sampling*
-aa	**-ab**	**-ad**	**-ar**	**- as**
0.05	10	4096 8192*	1024	2048 4096*

**) dynamic simulation settings*

table 9: The used Radiance/Accelerad parameters in both static and dynamic daylighting simulation. Other parameter values are taken over from Honeybee's standard settings.

point-grid wall offset [mm]	*point-grid spacing [mm]*	*point-grid floor offset [mm]*	*ceiling height [mm]*	*no. of floors [-]*
500	200	850	2700	23 / 5

table 10: Geometry settings for the definition of the Radiance/Accelerad sensor grid.

Figure 20: A flowchart showing the process of selecting the different urban locations and building the Rhino/HB model from the data. The underlaying data is from PDOK (2022), 3DBAG (2022), RVO (2022) and BGT (2022)

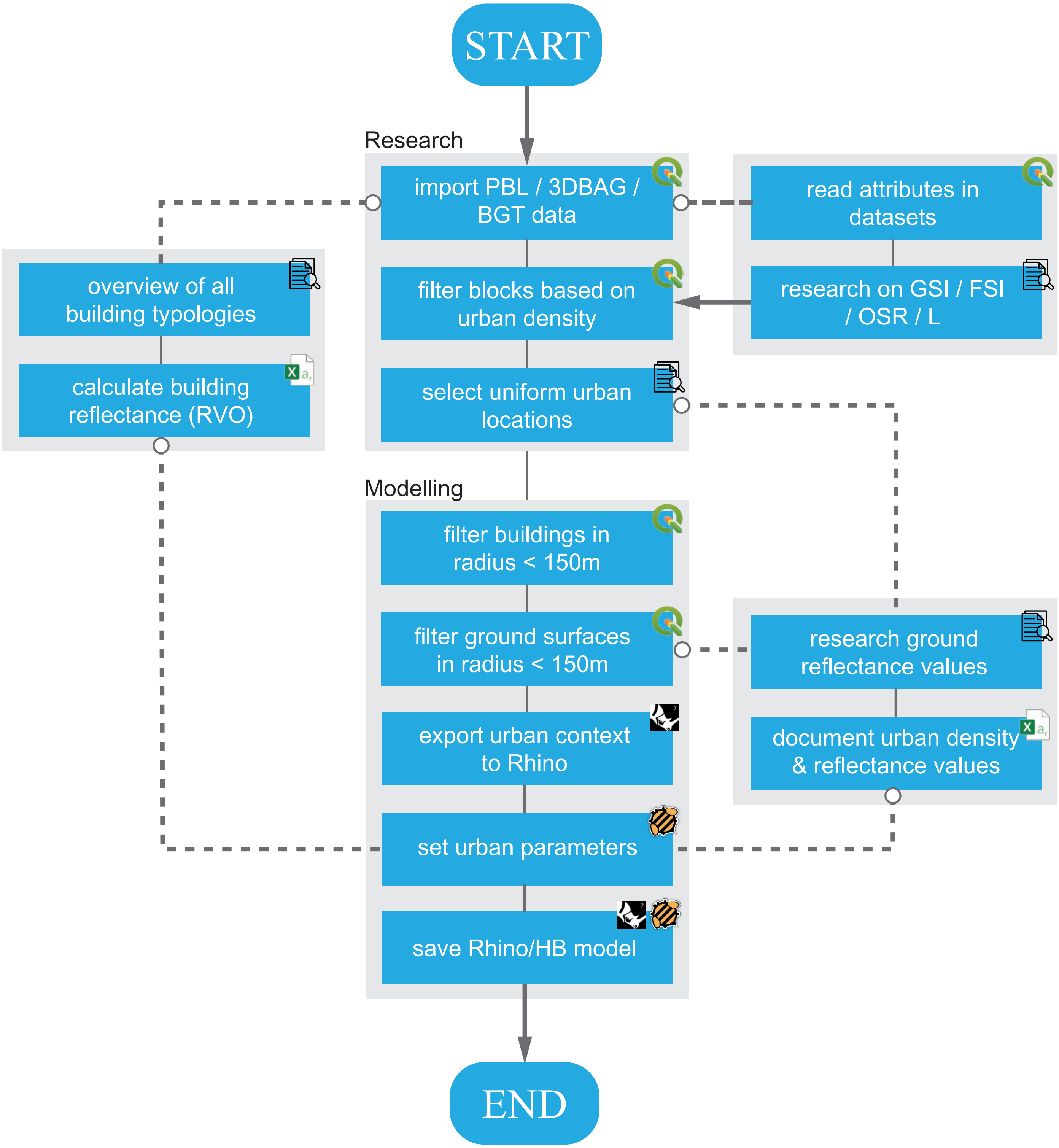


Figure 21: A flowchart showing the process of running static and dynamic daylighting simulations.

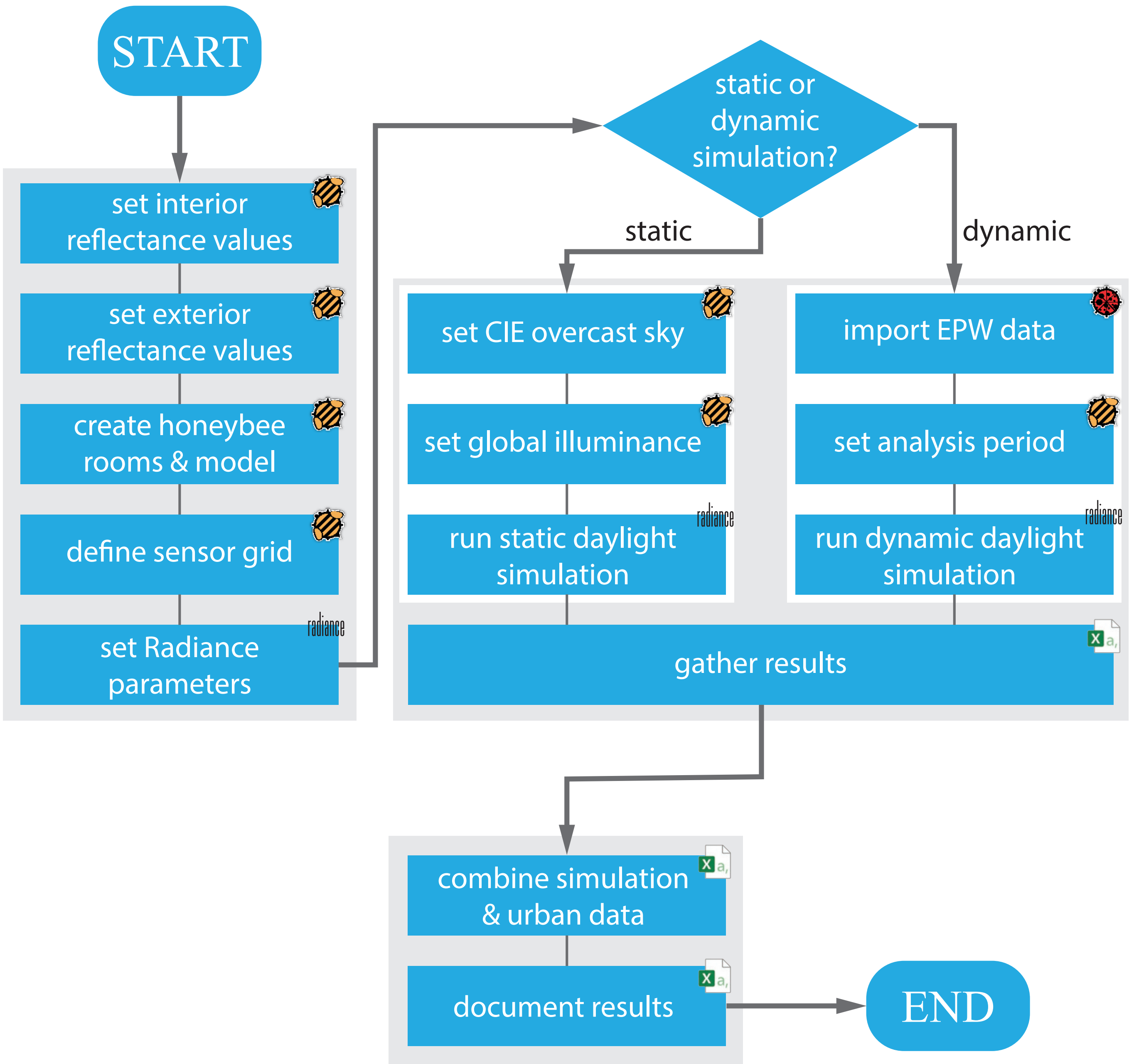
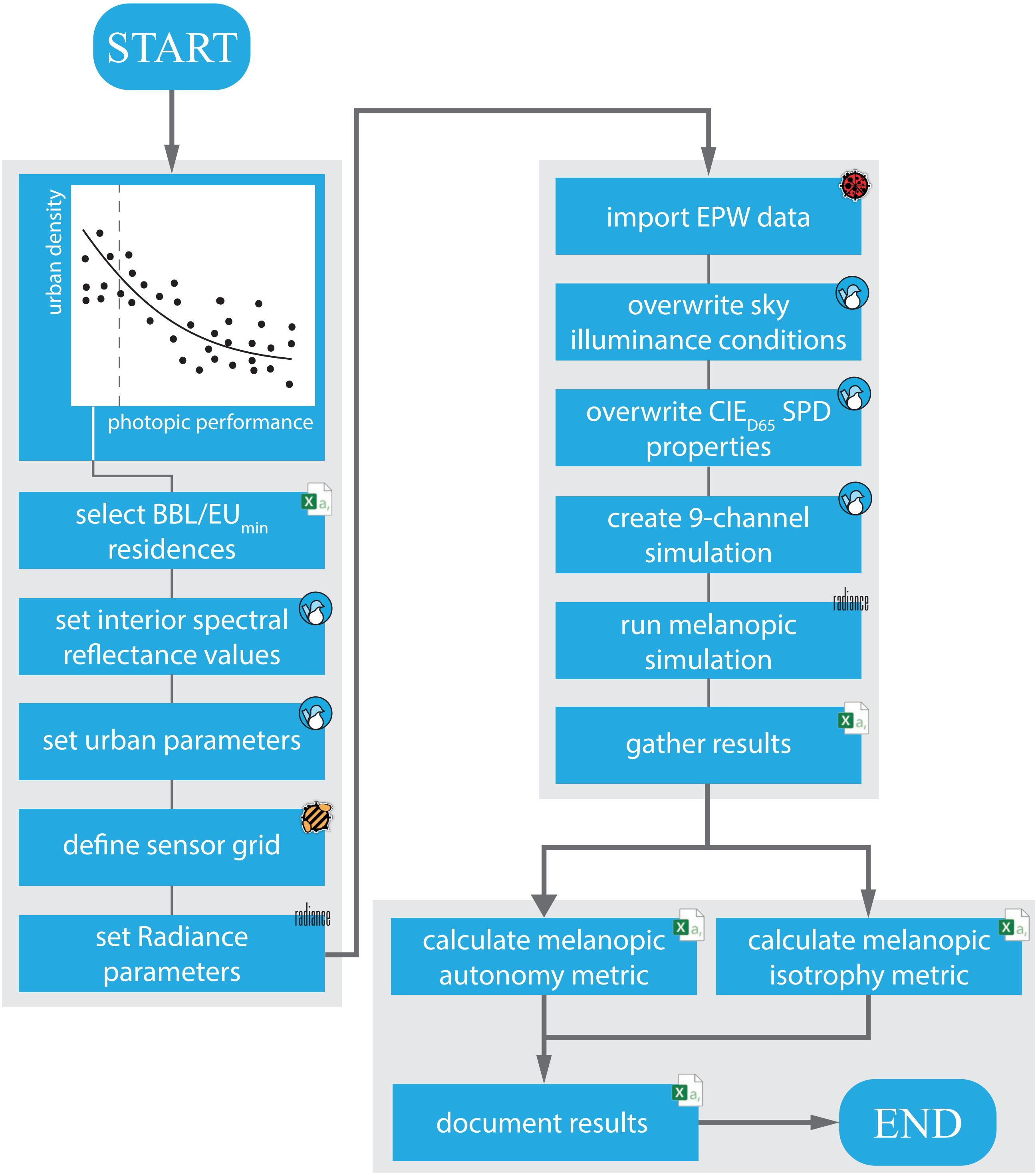


Figure 22: A flowchart showing the process of running point-in-time melanopic simulation using the LARK plugin for Grasshopper to run Radiance simulation for 9 channels.



Melanopic illuminance simulation

Generic Radiance simulation with Honeybee is computing photopic illuminance values but for the melanopic assessment the non-visual illuminance values are necessary. This can be simulated using the LARK plugin for Rhinoceros 7 and Grasshopper.

Because the direction in which a person is looking can influence the melanopic light exposure significantly (Altenberg Vaz & Inanici, 2020) the melanopic illuminance is simulated for the position of the eye. The illuminance values will be simulated in the vertical plane. The point-grid spacing is increased to 1000mm in melanopic simulation, and the point-grid floor offset is increased to 1200mm. This is to represent the height of the eye when seated. For all sensor points, melanopic light exposure is assessed in four directions, orthogonal with the room orientation.

In order to assess the spatial performance of melanopic illuminance, two new metrics are introduced. The Melanopic Autonomy (MA) and Melanopic Isotropy (MI) are both used to assess the quantity of melanopic illuminance in a room, as well as the 'flexibility' of view directions for sufficient melanopic exposure. The metrics are further explained in more detail on pages 45-48.

LARK requires detailed spectral data of materials to be defined, including the spectral power distribution (SPD) of the light source. For this thesis, the sun is the only light source but it is possible to simulate artificial lighting as well. For the SPD settings of the sky, CIE standard illuminant D65 (CIE, 2018) is used. This theoretical illuminant has a similar SPD curve to real-life measurements under sunny sky conditions. Hence why sunny days are assessed for this thesis. For different sky conditions, a different SPD has to be applied since the provision of circadian light is linearly correlated with the light efficacy of the sky (Andersen, Mardaljevic & Lockley, 2012) but for simplicity, this is disregarded in this thesis.

Sky view factor

It is expected that the sky view factor (SVF) has a correlation with daylighting performance. Therefore, the SVF is calculated for all simulated residences. The sky view factor is the percentage of sky dome visible from a given point. On the horizontal plane, the maximum value is 1.0 (unobstructed sky). In the vertical plane, i.e. on a façade, the maximum value is 0.5 (unobstructed sky). Mathematically a double oriented façade (type A) has a maximum SVF of 0.75.

Using the 'LB View percentage' component in Grasshopper, the hemisphere is split up in roughly 2300 vectors. Then, it is calculated for each vector if it has a free path to the sensor point. This results in a percentage of hemisphere visible (SVF) with a resolution of (100/2300=) 0.04%.

The SVF is calculated for all facades of the residences. The façade is split up in multiple sensor points with a spacing of 200mm, much like the sensor grid for daylighting simulation. For every façade, the average value is calculated which results in the SVF for that façade. For double oriented residences only, a faux separation wall is used to get a theoretical maximum SVF of 0.375 per façade: added together for a maximum of 0.75. Otherwise, the maximum value would be 1.0, which is not possible. This is graphically explained in Figure 23.

Due to sensor point offsets and limited resolution of the hemisphere, this method produced SVF values higher than 0.5 / 0.375 for a single oriented façade. To correct this, all sensor points values higher than 0.5 and 0.375 are replaced by their theoretical maximum. This correction had little to no effect on facades that had any obstruction (points did not exceed the threshold value), so the method of adjustment yields values are considered valid.

Hardware

All simulation is run on a desktop computer, running Microsoft Windows 10. The central processing unit (CPU) is an AMD Ryzen 7 3700X with 8 cores and 16 threads. The graphical processing unit (GPU) is a NVIDIA GeForce 3060 Ti with 8GB of VRAM memory. The active NVIDIA driver is version 538.68. In the system, 16GB of DDR4 memory was used but occasionally this was not sufficient during simulation and crashing would occur.

Using Accelerad, one simulation iteration (2x CBDM simulation & 1x static simulation, 9 residences, with context) took approximately 4.5 minutes for photopic simulation. Using regular Radiance, one melanopic simulation run (1x point-in-time static, 1 residence, with context, 9 channels) took approximately 1:30 minute. The SVF calculations were run sequential and took approximately 30 seconds for 12 façade faces (one building floor).

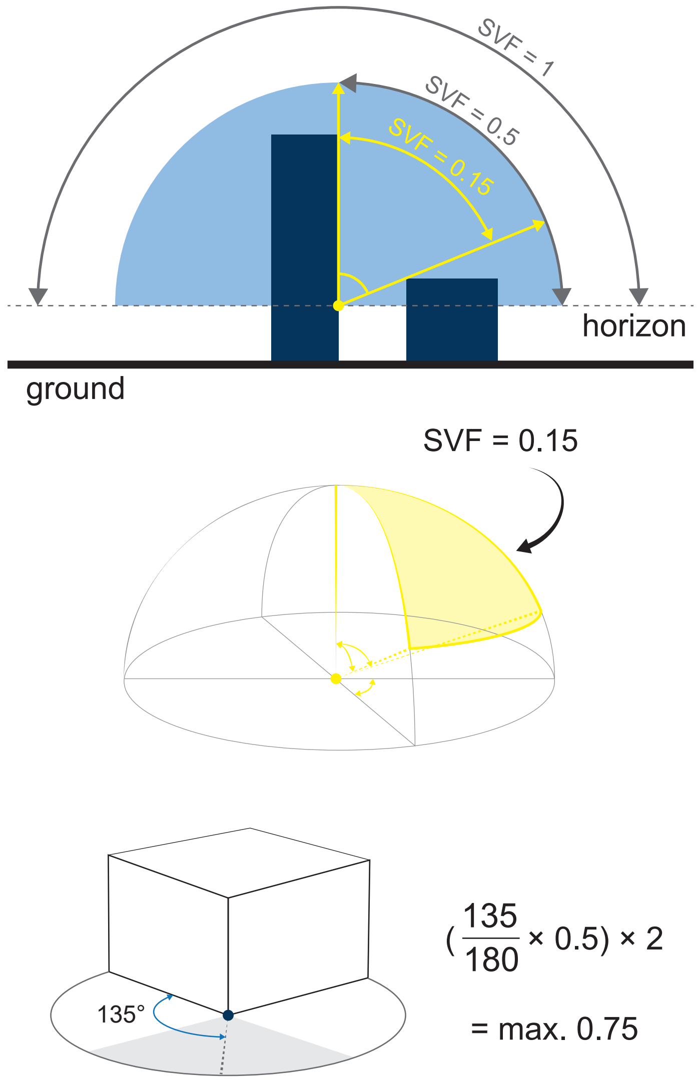


Figure 23: An explanation of the sky view factor (SVF) in the vertical plane, in relation to the built environment. Maximum SVF for a double oriented facade is 0.75. Own source.

research results

Performance on building scale

Type & orientation
In order to interpret the results of the simulation in urban context correctly, a baseline performance is simulated for all residential types. This has been done for both the standard layout (2 rooms) and the simplified layout (1 room). Both static and dynamic performance has been done.

The baseline performance in static simulation is sufficient to fulfil the BBL requirement (DF=1 for the 50th percentile) for all rooms, as can be seen in Figure 24. This is no coincidence: the facade properties of all rooms have been adjusted to comply to this requirement. The goal is to make the results of this thesis more reliable by simulating a building that is compliant to the BBL. The chalk line method has not been applied in the simulations.

Looking at the simplified interior layout, it performs better than the standard interior layout. This is mainly because the apertures in the bedroom are now increasing performance also for the rest of the occupied area, and not only the bedroom. The maximum performance comes close to the EU minimum (DF=2.1 for the 50th percentile and DF=0.7 for the 95th percentile) but only if the results are rounded up to 1 decimal.

In Figure 25 we can see the performance differences in dynamic simulation. Here, the orientation influences the residence performance because of the contribution of direct sunlight. To estimate the differences between multiple orientations, simulation is run for eight orientations. The 50th percentile performance is recorded in Figure 25 as well as the total annual illuminance per sensor point (TAI in klxh) in Figure 6. For the standard interior layout, the grids of both the bedroom and livingroom are merged together to conclude on performance.

In dynamic simulation, all residences fulfil the EU minimum recommendation of $DA_{300}\geq50$. The EU minimum recommendation for $DA_{100}\geq95$ is not recorded but generally this requirement is easier to comply to (Sepúlveda, De Luca & Kurnitski, 2022). In conclusion, it is possible for all orientations and all residences to fulfil the EU medium requirement ($DA_{500}\geq50$). What stands out is the type A residence, benefitting from its double-oriented facade, complying in all cases to EU high recommendation of $DA_{750}\geq50$, which is impressive in Dutch context.

Comparing the static simulation with the dynamic simulation, the dynamic DA recommendation is easier to comply to for all residences. This is surprising since both methods are allowed to assess daylighting performance according to the EN 17307 and BBL. The residences with standard interior layout are struggling for BBL minimum performance in static simulation and the simplified layout just-about reaches the EU minimum threshold. There is an over-estimation of performance in dynamic simulation, or an under-estimation in static simulation for all residences.

As for performance differences between the standard and simplified interior layout, the simplified layout performs better for types B and C in dynamic simulation and equally for type A (Figure 26). In static simulation, it is more complex with the simplified layout performing better than the livingroom but worse than the bedroom (Figure 24).

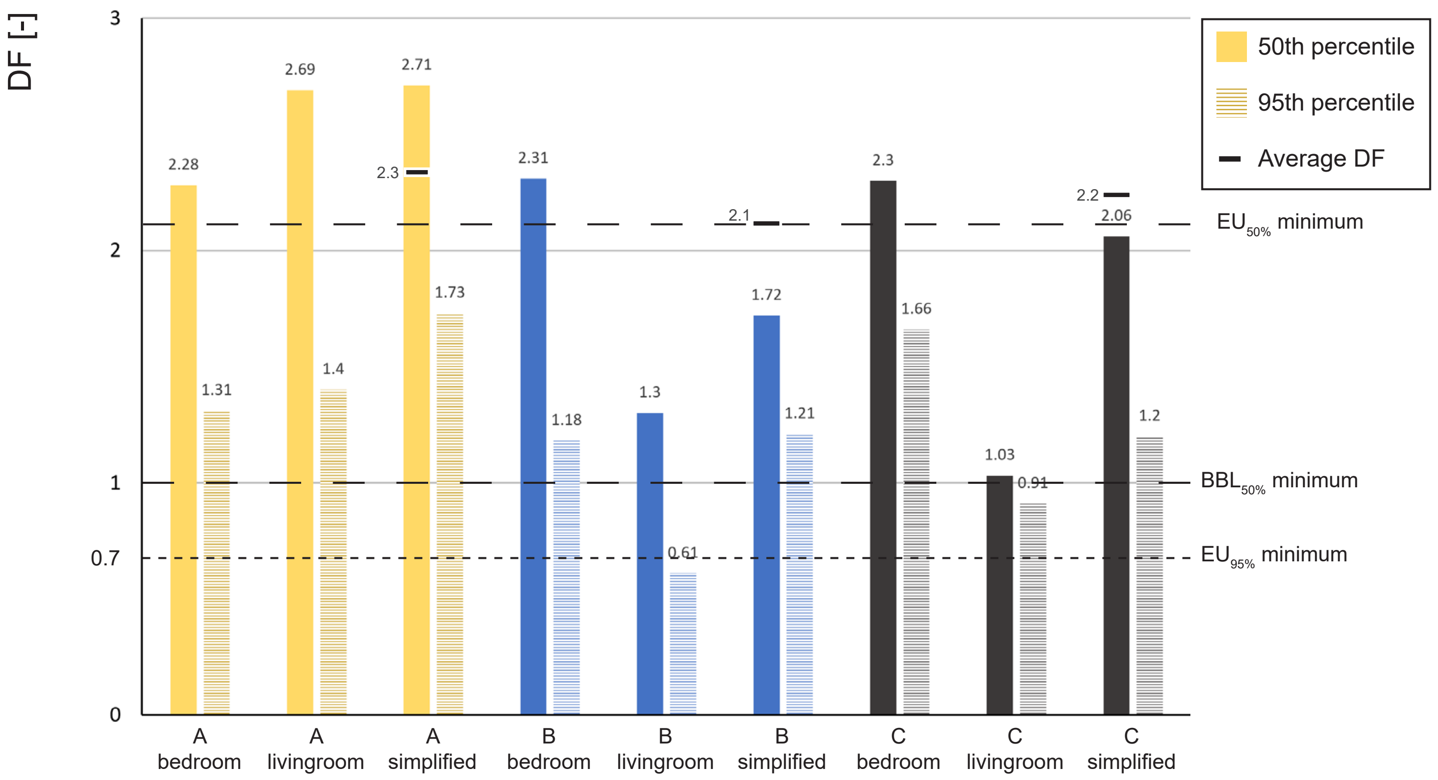


Figure 24: Daylight factor (DF) performance of different residence, for the 50th & 95th percentile. No obstruction is modelled in the simulation. Own source.

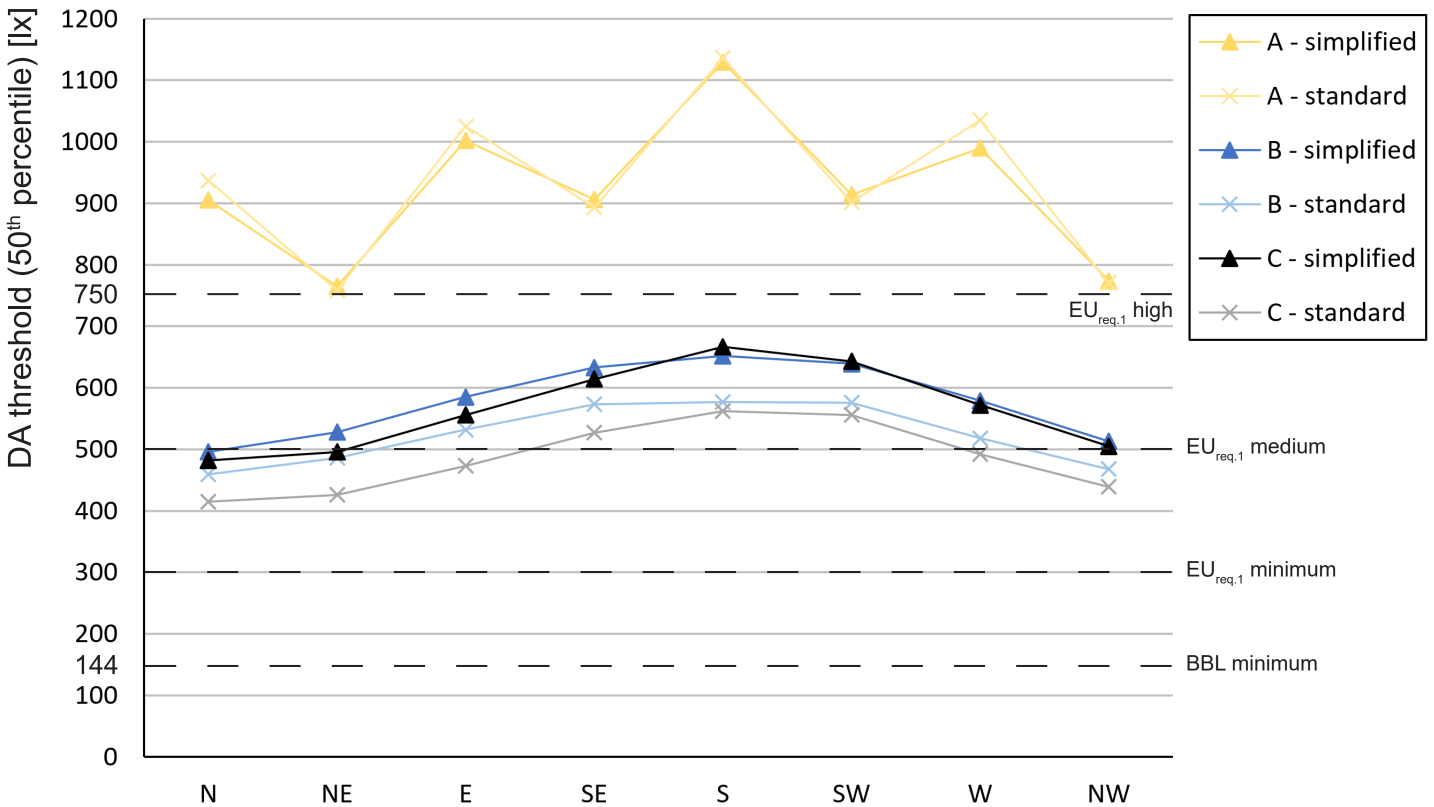


Figure 25: Daylight autonomy (DA) threshold performance of different residence for the 50th percentile. No obstruction is modelled in the simulation. Own source.

Later in the report, the TAI metric is used as a continuous measure of performance in dynamic simulation. Hence, the theoretical maximum TAI values are simulated for all residences.
The TAI metric shows a similar course of performance as Figure 25, with type B and type C residences performing relatively similar and type A profiting from its double-oriented facade. However, percentage-wise, the three residences perform more similarly. The performance differences are not as large as in the 50th percentile performance from Figure 25. This is recognized in Figure 26 at the SE and SW orientation: TAI performance is only spread ca. 20%. DA threshold performance on the other hand is much more spread with a difference of ca. 80% in threshold values (Figure 25).

Again, the simplified layout performs better than the standard interior layout for types B and C, and it is any result for type A. In Figure 27 the relative performance change is plotted for all orientations. The zero line represents the simplified layout performance. Type C is the most impacted by the standard layout with a performance reduction of ca. 15%. Type B is less impacted with a performance reduction of ca. 5%. Type A performance is reduced with only ca. 3% for SE, S, SW and W orientation (the ones that receive direct sunlight).

In conclusion, the TAI metrics is following the same trend as the DA threshold performance across different orientation. A difference is that the results are more close together than the DA threshold would suggest. Type A seems to be able to convert TAI better into DA threshold performance. The TAI decrease is ca. 15% for type C, ca. 5% for type B and ca. 3% for type A if there is direct sunlight. For the remainder of the study, the simplified layout will be used in simulation but it should be noted that actual real world performance can vary with at least 15%, purely based on the interior layout.

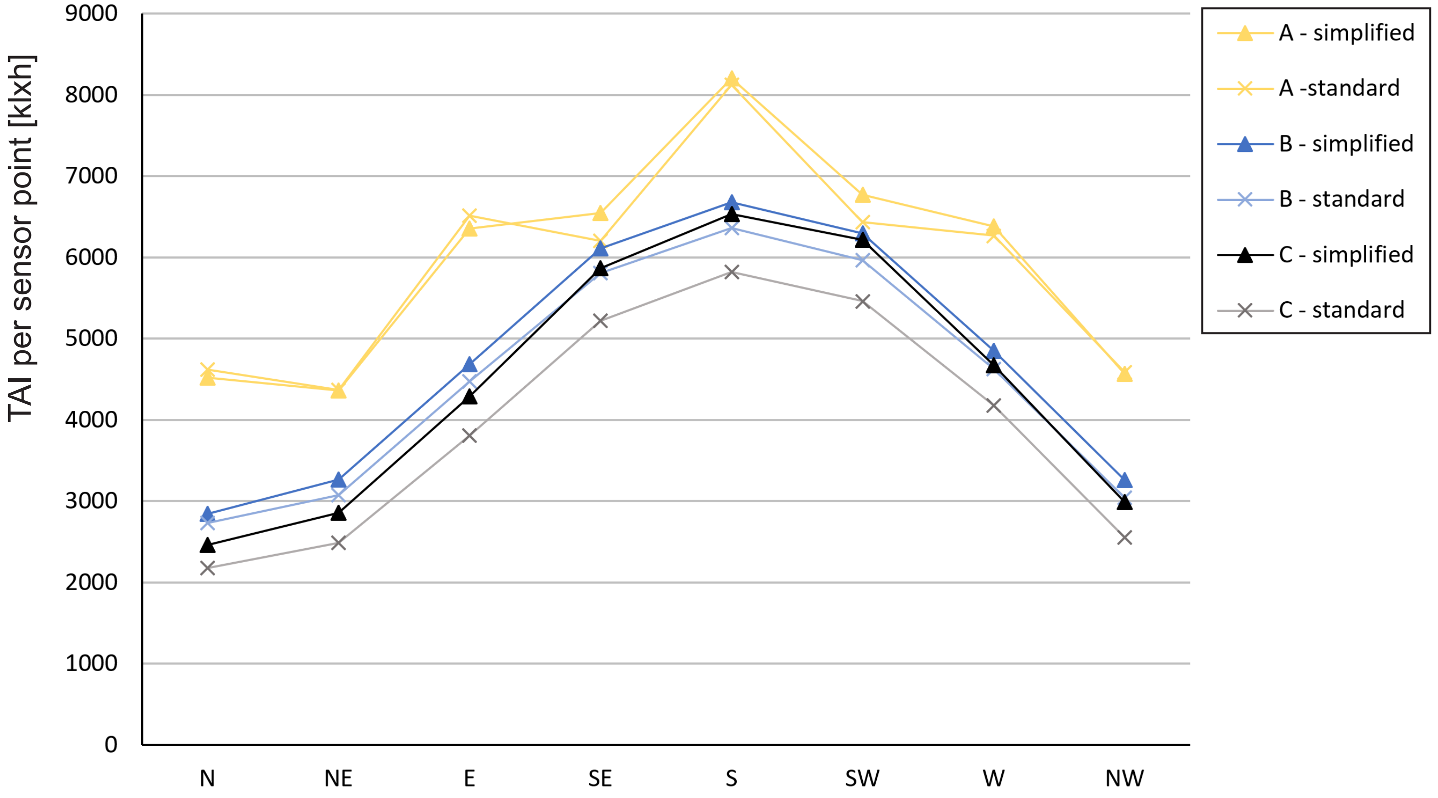


Figure 26: Total annual illuminance per sensor point (TAI) performance of different residences in eight orientations. No obstruction is modelled in the simulation. Bedroom/livingroom values are averaged. Own source.

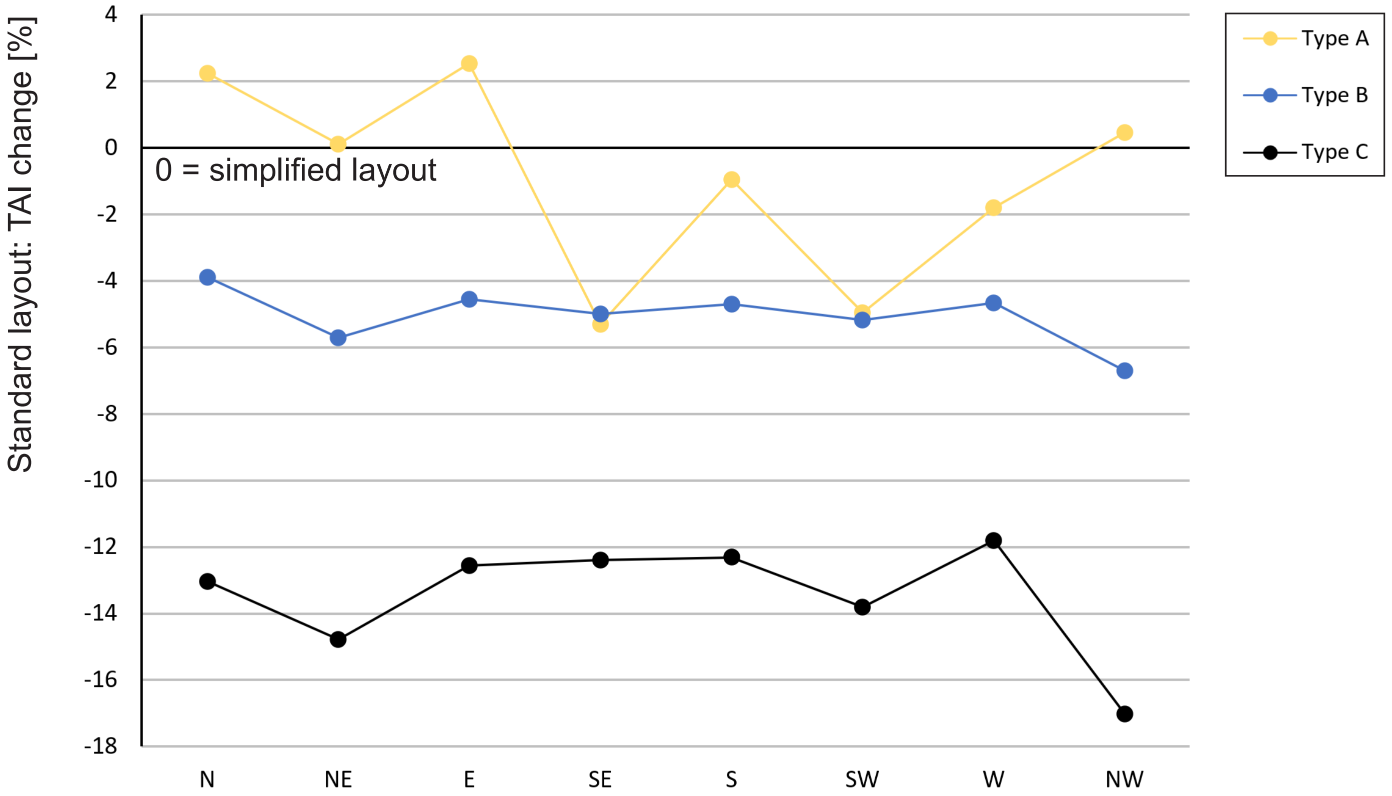


Figure 27: The performance change (TAI) of the standard layout, compared to the simplified layout. Zero change means identical performance to the simplified layout. Own source.

Interior reflectance values

This study requires detailed (and consistent) reflectance properties of materials to reflect a degree of realism in the simulation. Therefore, materials with known photopic and melanopic reflectance values are chosen (table 8). This is important to make the results comparable between the photopic and melanopic assessment. Since the EN 17037 as well as the NPR 4057 prescribe reflectance values that are lower than the reflectance values in this thesis, the impact of interior reflectance values is assessed.

For accordance with the EN 17037, the reflectance values must fall within a lower and upper bound for each face type. Depending on the chosen reflectance values, they are closer to the lower or higher bound and the simulation results may vary. The BBL dictates the reflectance values of the EN 17037's lower bound to be used for the building permit. Thus, the EN 17037 results can be read as if they were the BBL results.

To investigate the sensitivity to interior reflectance values, multiple residences have been simulated with different interior reflectance 'sets'. The values can be found in table 11. Each set of reflectance values uses different values for all surfaces. The 'thesis standard' set contains the materials as used in the rest of the study, including the melanopic assessment.

The simulation is done for three building floors in Amsterdam context, for both static and dynamic simulation. The ground floor, the 10th floor and the top (23rd) floor are assessed. Eight residences are simulated per floor and the results have been normalised to exclude the impact of orientation and residential type. The continuous performance metrics are used which are the average daylight factor (DF_{avg}) and total annual illuminance (TAI). The 'thesis standard' set is considered the baseline performance. Because the results are normalised, the different results for orientations do not reflect the impact of orientation itself but rather the location in the standard residential tower.

In Figures 28a to 28f, the DF_{avg} increase or decrease is convincing and measurable. The EN 17037 higher bound sees an increase in DF_{avg} of 5-10% compared to the thesis standard set. The EN 17037 lower bound sees a decrease of 5-15% in DF_{avg}. The change in performance is across all orientations, suggesting that interior reflectance correlates linear with performance.

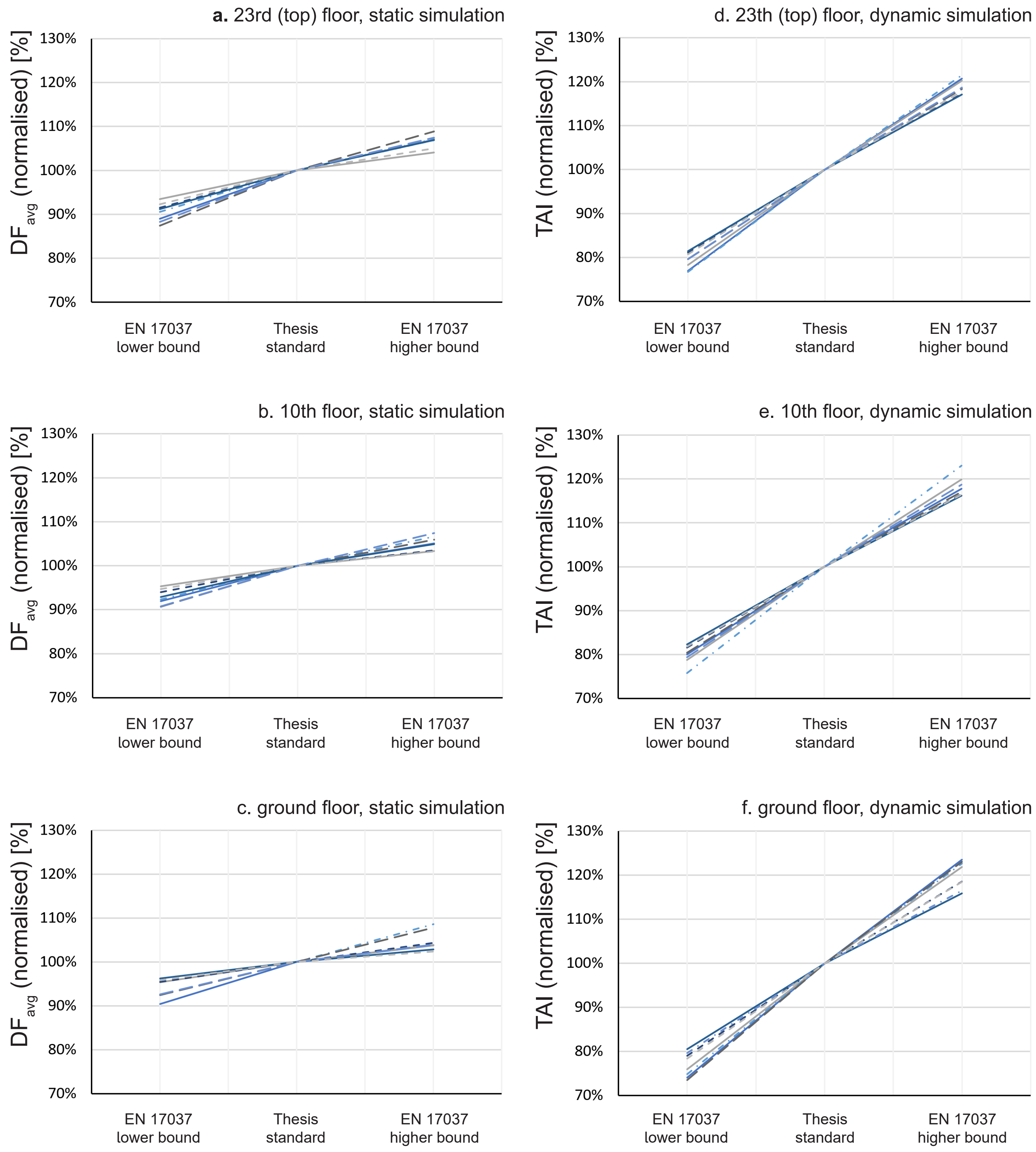
In dynamic simulation, the TAI performance is more impacted drastically as can be seen in Figure 28c to 28f. The EN 17037 higher bound performs 15-25% better compared to the thesis standard set. The EN 17037 lower bound sees a decrease of 15-25% in TAI performance. The performance change is happening across all orientations.

The DF_{avg} performance of the EN 17037 higher bound is 30% higher compared to the EN 17037 lower bound. This is significant and can result in an increase of up to 10% in $DF_{2.1}$ performance, reading from Figure 28a and 28c. It should not be underestimated that changes the reflectance values can swing the static simulation results significantly.

In dynamic simulation, the EN 17037 higher bound performs up to 67% better than the EN 17037 lower bound. This is in the same order of magnitude as adding a second facade to a type B or C residence, or the difference between a north and south oriented residence. The set of interior reflectances is therefore crucial for daylighting designers and architects to keep realistic: real world performance can be different than the simulated situation if the values are not considered carefully.

layer	*EN 17037 lower bound*	*thesis standard*	*EN 17037 higher bound*
ceiling	0.70	0.88	0.90
interior walls	0.50	0.54	0.80
flooring	0.20	0.36	0.40
exterior	0.20	varies	0.40

table 11: An overview of different set of interior reflection values. Values are taken over from the EN 17037 (2018).



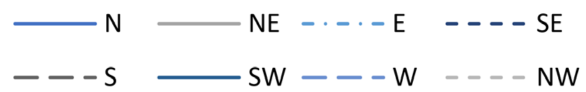


Figure 28.a-f: The normalised performance change for different reflectance sets. The reflectance values of the thesis are indexed as 100%. For static performance, average DF is used for comparison. For dynamic performance, TAI is used for comparison. Both metrics are normalised.

Photopic transmission values

Now that the performance sensitivity to interior reflectance sets is known, the next focus of attention are other aspects of the simulated residences. The glazing system that is used in all simulations is a coated triple glazing system but in real practice other types of glass are often applied as well.

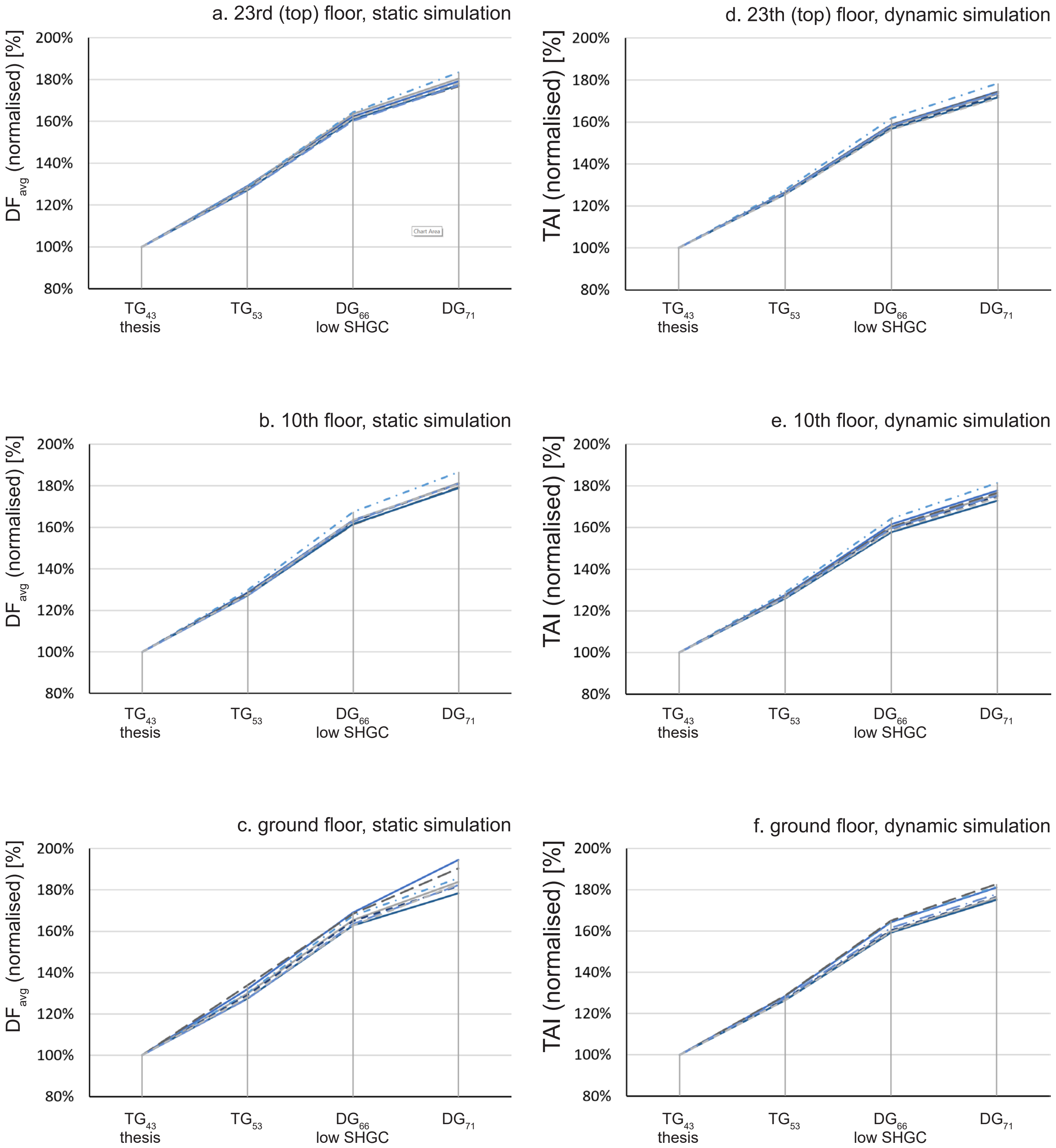
With a photopic transmission percentage of 42.8%, the triple glazing system of this study is on the low side. This is on purpose to assess a 'worst case scenario' but we are interested in the effect of interchanging this for another system that might be cheaper, has a higher light transmission or is more lightweight. Accordingly, 4 types of glazing have been compared for their performance in static and dynamic simulation in Amsterdam context.

Four different glazing systems have been tested on performance. Two triple glazing systems (TG) are tested as well as two double glazing systems (DG). Both TG systems are fabricated by Pilkington (2022) and have a coated pane with a neutral transmission curve. The DG systems are fabricated by AGC (2023). The choice for product by these manufacturers is because they provide detailed information on their glazing systems and their glazing properties are recorded in the international glazing database (IGDB, 2023). One of two variants has low SHGC properties and the other is optimised for light transmission. All system properties are calculated with WINDOW 7.8 software (LBNL, n.d.). Detailed system properties can be read in appendix 5. The window mullions and dimensions are kept identical throughout all simulations.

The simulation is done for three building floors in Amsterdam context, for both static and dynamic simulation. The ground floor, the 10th floor and the top (23rd) floor are assessed. Eight residences are simulated per floor and the results have been normalised to exclude the impact of orientation and residential type. The continuous performance metrics are used which are the average daylight factor (DF_{avg}) and total annual illuminance per sensor point (TAI). The 'TG thesis' glazing is considered the baseline performance.

Looking at the results in Figures 29a to 29f, the increase in transmission value has a great impact on performance for both static and dynamic simulation. Changing out the glazing systems for another behaves predictable and consistent across all floors and orientations. An example of this is a transmission increase from 43% to 53% (+23% more transmissive) resulting in a performance increase of ca. 25-30%. In conclusion, increasing the glazing transmission value for more performance seems very effective.

Using the DG system with a transmission value of 71% results in a performance increase of ca. 75%. A performance increase of this order of magnitude is sufficient to offset any loss in performance due to orientation or interior layout. However, the possibility to apply a DG system is not always obvious. The light transmission value of glazing systems is known to have a relation with SHGC values, thermal comfort, energy performance and acoustic performance. Therefore, glazing systems should still always be selected with care.



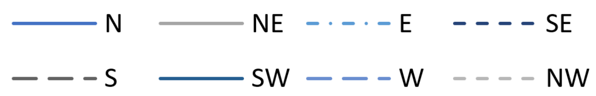


Figure 29.a-f: The normalised performance increase for different transmission values. The transmission of ' TG thesis' is indexed as 100 %. For static performance, DF_{avg} is used for comparison. For dynamic performance, TAI is used for comparison.

Assessment of daylighting performance

Static DF simulation

Both static and dynamic simulation is run for all residences in six different urban locations. First, the results from the static simulation are discussed. These are the results that can be used to assess performance according to the first method of the EN 17037 (which is also used in the BBL).

The residences that are simulated in this thesis fulfil the BBL requirement of DF=1 for the 50th percentile. They also fulfil the EU minimum requirement of DF=0.7 for the 95th percentile but only with a small margin. Hence it is expected that not many residences will fulfil the thesis recommendation of DF=2.1 for the 50th percentile.

A look at the results in Figures 30a to 30f reveals that none of the residences fulfil the thesis recommended daylight factor of 2.1 for 50% of the floor area. The maximum percentage is ca. 45% in all cities. It seems that the upper limit of performance is due to the residence's (facade) layout: design alterations are necessary to fulfil the thesis recommendation. However, for some residences it would still be difficult to achieve sufficient performance, even with adjustments.

In static simulation, orientation should not impact performance of residences because of the uniform sky conditions. Yet there are large differences in the simulation results as can be seen in figures 30a to 30f. These differences can be explained by residential type (double oriented residences perform better) or the obstruction. This stresses the importance of other aspects than orientation in static daylighting simulation.

The maximum $DF_{2.1}$ performance is observed for the uppermost building floors for Amsterdam and Rotterdam Maritime but at much lower building floors for other urban areas. It is clear that more dense urban areas affect DF performance more heavily. Because none of the residences fulfil requirement, it is not possible to recommend at what building level the performance is adequate. However, we can express the loss in performance with the use of a continuous performance indicator: the average DF percentage (DF_{avg}).

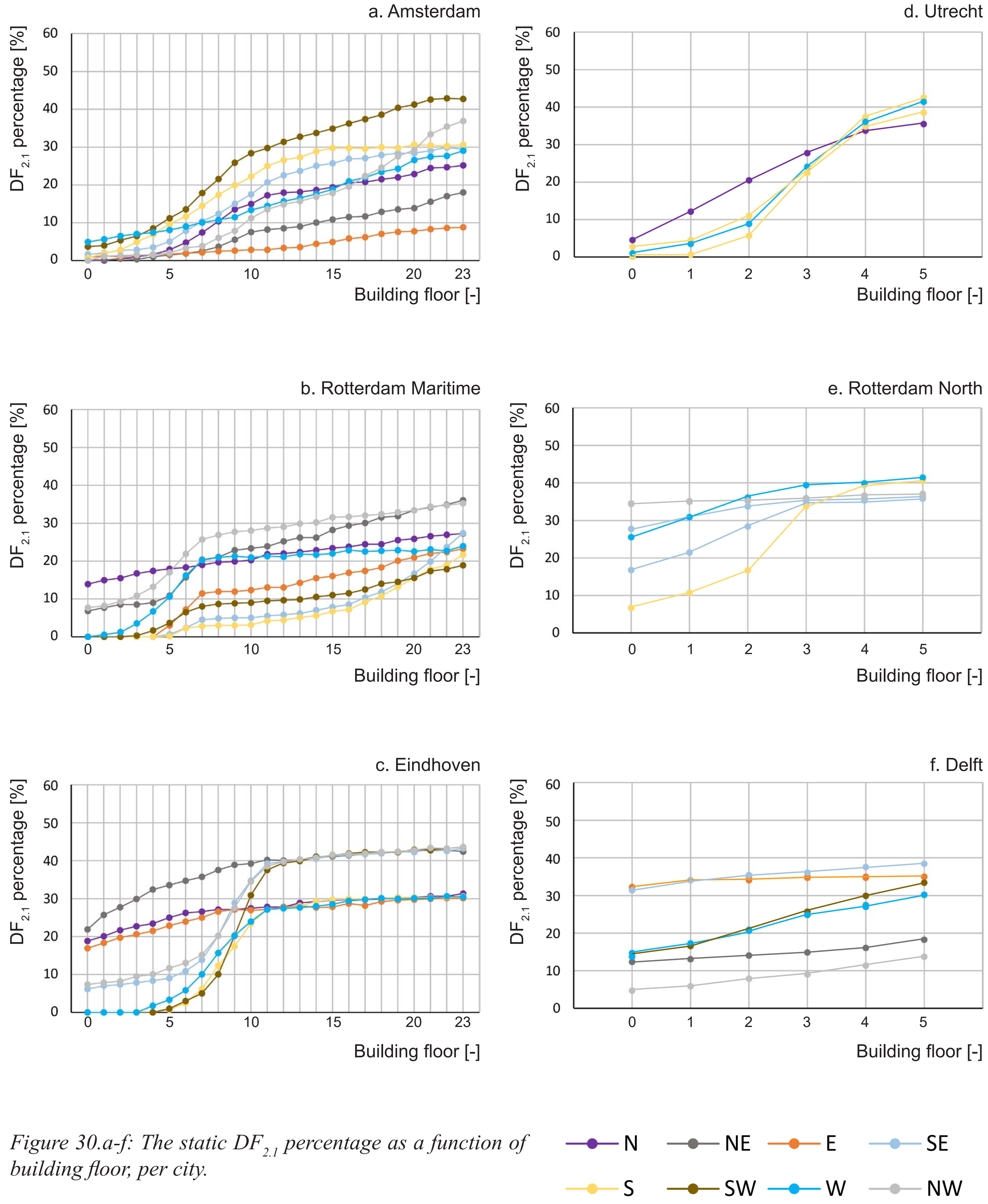


Figure 30.a-f: The static $DF_{2.1}$ percentage as a function of building floor, per city.

In Figures 31a to 31f, the average DF is plotted and normalised to their maximum performance respectively. This would be DF=2.3 for type A, DF=2.1 for type B and DF=2.2 for type C as can be read from Figure 24. By doing this, it is possible to make assumptions on performance decrease, in this case as a function of the building floor. In Figure 31a to 31f we see that the results are better pronounced than in the previous Figures. We can also see that the residences are approaching 100% of their potential maximum static performance, confirming that the residences are designed with too little headroom to fulfil the thesis requirement in urban context.

Just like in the Figures 30a to 30f, there are large differences between different orientations in the static simulation. This can be explained by different obstructions and residential types in the simulations. The most heavily obstructed orientations are easily recognized by their lowest performance: for example the west, south-west and south orientation in Eindhoven which are close across a building of 11 floors (Figure 31c).

Some trends do still persist in the DF_{avg} performance Figures. The orientation of a residence should not be a factor in static simulation but the spread is still large even though the results are normalised. We conclude that other factors are at play and determine the performance of a residence. This issue seems to be more present in high-density urban areas such as Amsterdam, Rotterdam Maritime but the spread in Utrecht is also relatively large. It is suspected that either obstruction or certain urban density characteristics cause this performance spread.

In conclusion, it is clear that static daylighting performance decreases in urban areas. The theoretical maximum value is approached but [reference line to how much performance decrease per city is expected]. With no headroom in the design of the residence, it is very possible that none of the residences will fulfil the thesis recommendation of $DF_{2.1} \geq 50$ in urban context. The spread of performance is seemingly larger for heavily obstructed urban areas or urban areas with certain density characteristics. Hence, further analysis needs to be performed to confirm this preliminary finding.

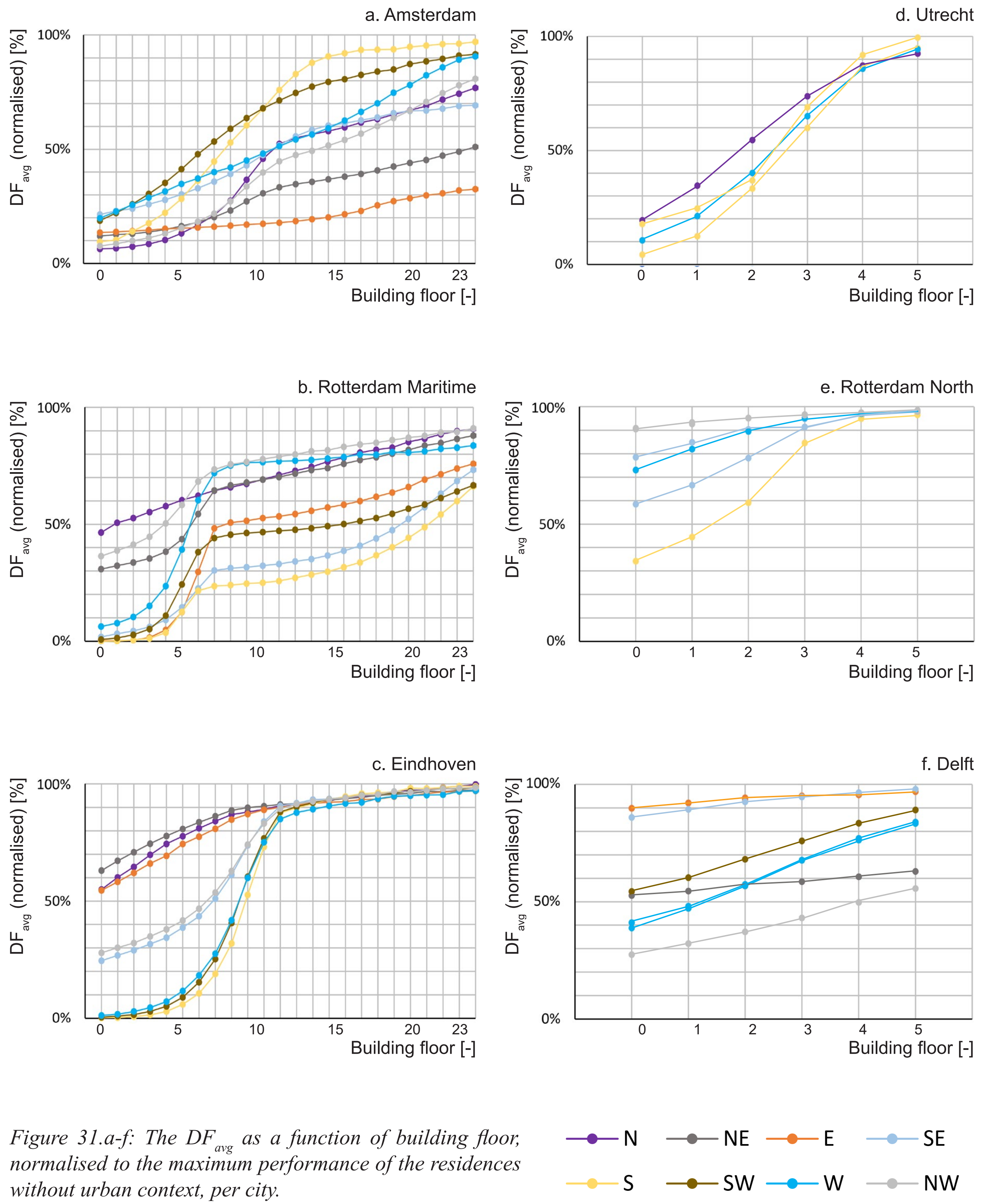


Figure 31.a-f: The DF_{avg} as a function of building floor, normalised to the maximum performance of the residences without urban context, per city.

First off, static performance is assessed as a function of the sky view factor (SVF). Previously, we concluded that the spread in performance can be caused by heavy obstruction or other urban density characteristics. Therefore, we look at the SVF value to see if this holds true.

For each residence type, the mean static performance is plotted as a function of the SVF. The SVF values are binned in order to allow for the calculation of mean values and standard deviation. The error bars are +/- 2 standard deviations (SD). If there is no normal distribution in the results, at least 75% of the points fall in the range of +/- 2 SD (Chebychev's theorem, Chebychev, 1867). Consequently, the probability of a point falling outside this range is at maximum 25%.

In Figures 32a to 32c we can see the results. We can see that the mean performance increases with each SVF bin, meaning there is a correlation to be found. It confirms that residences with a low SVF have a 75% probability that they will perform insufficient, independent from building floor. In other words, heavily obstructed residences will perform worse than ones without obstruction.

In conclusion, static performance is decreased for residences with a low SVF value. This can explain why the performance spread is larger for higher density urban areas. No SVF threshold value can be given that ensures sufficient daylighting (with p=75%) due to the design of the residences but it might be possible for dynamic daylighting performance that generally perform better. An advantage of the SVF indicator is that it is independent of orientation and building level, making it a useful early design stage indicator for performance.

The DF performance assessment is useful and more accurate in lower-density areas with little obstruction. Those are the situations where the EN 17037 first method is most truthful. For higher density areas, the first method of the EN 17037 results in performance loss of up to 70% if context is integrated in the methodology.

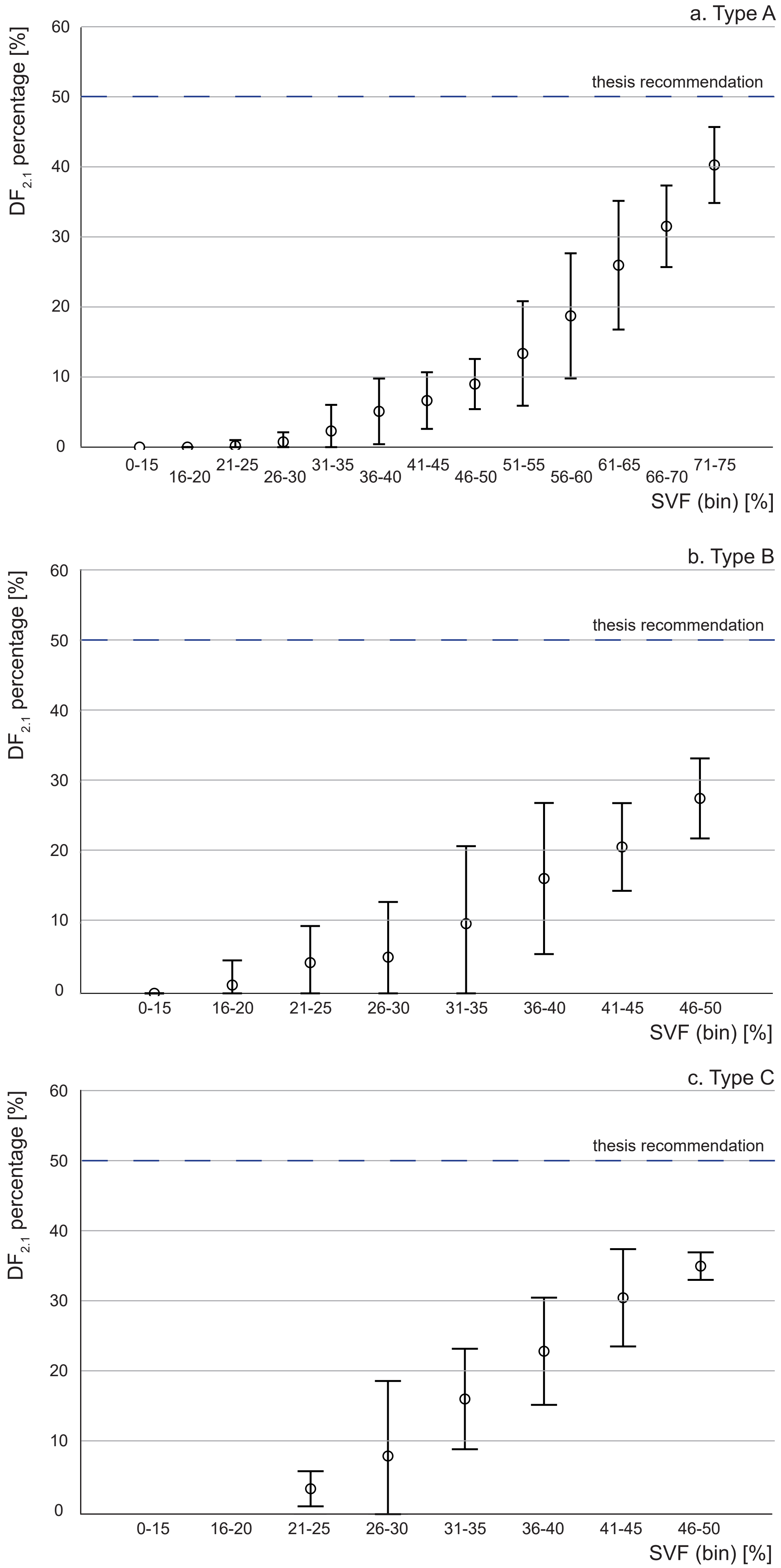


Figure 32.abc: The mean $DF_{2.1}$ percentage as a function of SVF, binned. Bin size is 5%. Error bars represent +/- 2 SD for 75% certainty (Chebychev, 1867).

Dynamic DA simulation

In the results of the dynamic simulation, the thesis recommendation ($DA_{300} \geq 50$) is fulfiled in many cases as can be seen in Figures 33.a-f. In all cities there are residences that do and do not fulfil requirement. What they have in common is that generally speaking, the insufficient residences are on the lower building floors. At the same time, exceptions can be found the higher floors in Amsterdam and Rotterdam Maritime that perform inadequate (Figures 33a and 33b).

A difference between static and dynamic simulation is that orientation influences performance in dynamic simulation. This is recognized in the results accordingly, where better orientations perform better if the context allows for it. An example of this is the south-west residence in Amsterdam (Figure 33a). Well oriented residences, in combination with little obstruction, fulfil requirement on lower floors as can be seen in Rotterdam North (Figure 33e). On the other hand, 'bad' oriented residences with little obstruction can also fulfil requirement (Figure 33c).

Yet there are situations where a well oriented residence does not fulfil the thesis requirement. Based on the dynamic simulation results alone, it is hard to conclude on performance decrease in dynamic simulation as a function of urban density or building floor.

However, medium-density urban areas tend to achieve higher performance at lower floor levels. At building floor 5, performance is increased to $DA_{300} \geq 50\%$ for Utrecht, Rotterdam North and Delft, while in the other cities it is still only at 10% compliance (Figure 33a-c). The spread of performance is also much larger for the higher density areas, ranging from 0% all the way up to 90%. We can conclude that other aspects such as orientation and obstruction are at play, similar to what is found in static simulation.

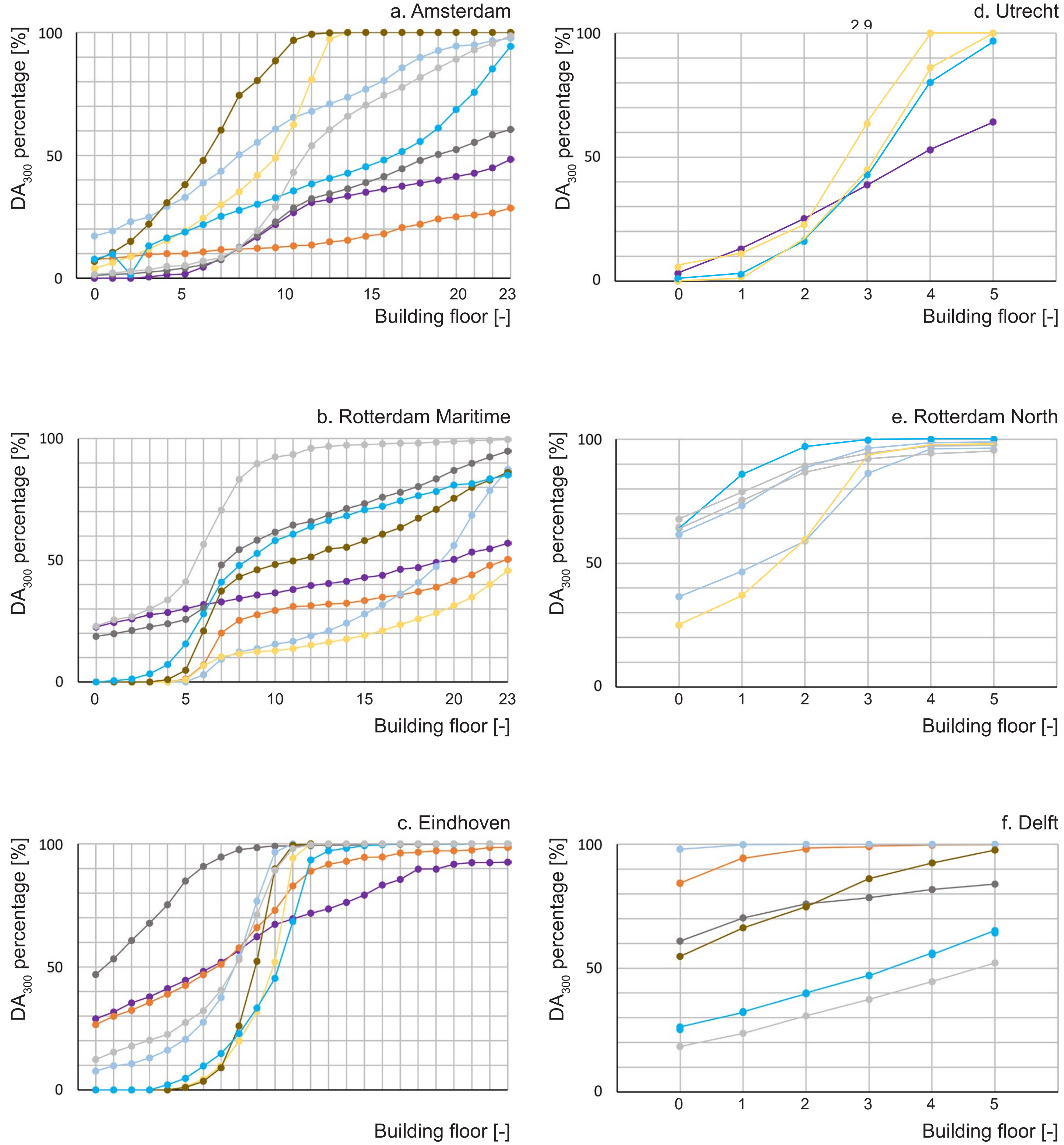


Figure 33.a-f: The DA_{300} percentage as a function of building floor, per city.

In Figures 14a-c, the mean DA_{300} performance is plotted as a function of the SVF with bin size 5%. Again, the error bar is shown as +/- 2 SD for 75% probability the points fall within this range (Chebychev, 1867).

Reading from the Figures: to fulfil the thesis recommendation of $DA_{300} \geq 50$, for type A a SVF of 56-60% is recommended, for type B 46-50% and for type C 41-45%. This is with a probability of 75%. Adversely, there is a 75% probability risk that the thesis recommendation will not be achieved under a SVF of 41-45% for type A, 31-35% for type B and for 31-35% for type C.

The daylight autonomy for similar SVF values is the best for type C, followed by type B and finally for type A. The performance of type C seems to be less impacted by obstruction than type B: maybe because type C does not have a loggia built in. For type A, the floor surface area is bigger hence the lower performance for similar SVF. However here it should be noted that a higher SVF is easier to be reached for a double oriented facade.

Looking at the spread of results, it stands out that the performance spread is larger, compared to the static performance results. This is caused by orientation and direct sunlight playing a part in dynamic daylighting simulation. Surprising however is that the spread of type B is bigger than that of type A or C. With 288 data entries, the spread of type B is not comparable to type A with 336 data entries. It could be possible that type A, because of its double oriented facade, is less sensitive for orientation, explaining why the performance differences may be smaller (with a lower SD as a result). This assumption can be confirmed by looking at the results in Figure 26 where the percentage differences between the best and worst orientation are smaller for type A.

In conclusion, plotting dynamic performance as a function of the SVF leads to concrete recommendations for all residential types. Minimum SVF threshold can be identified to fulfil the thesis recommendation with 75% probability, which is acceptable. In reverse, it also leads to recommendations where there is a risk of at least 75% that the thesis recommendation will not be achieved. This is already useful information that can be used for concrete design recommendations.

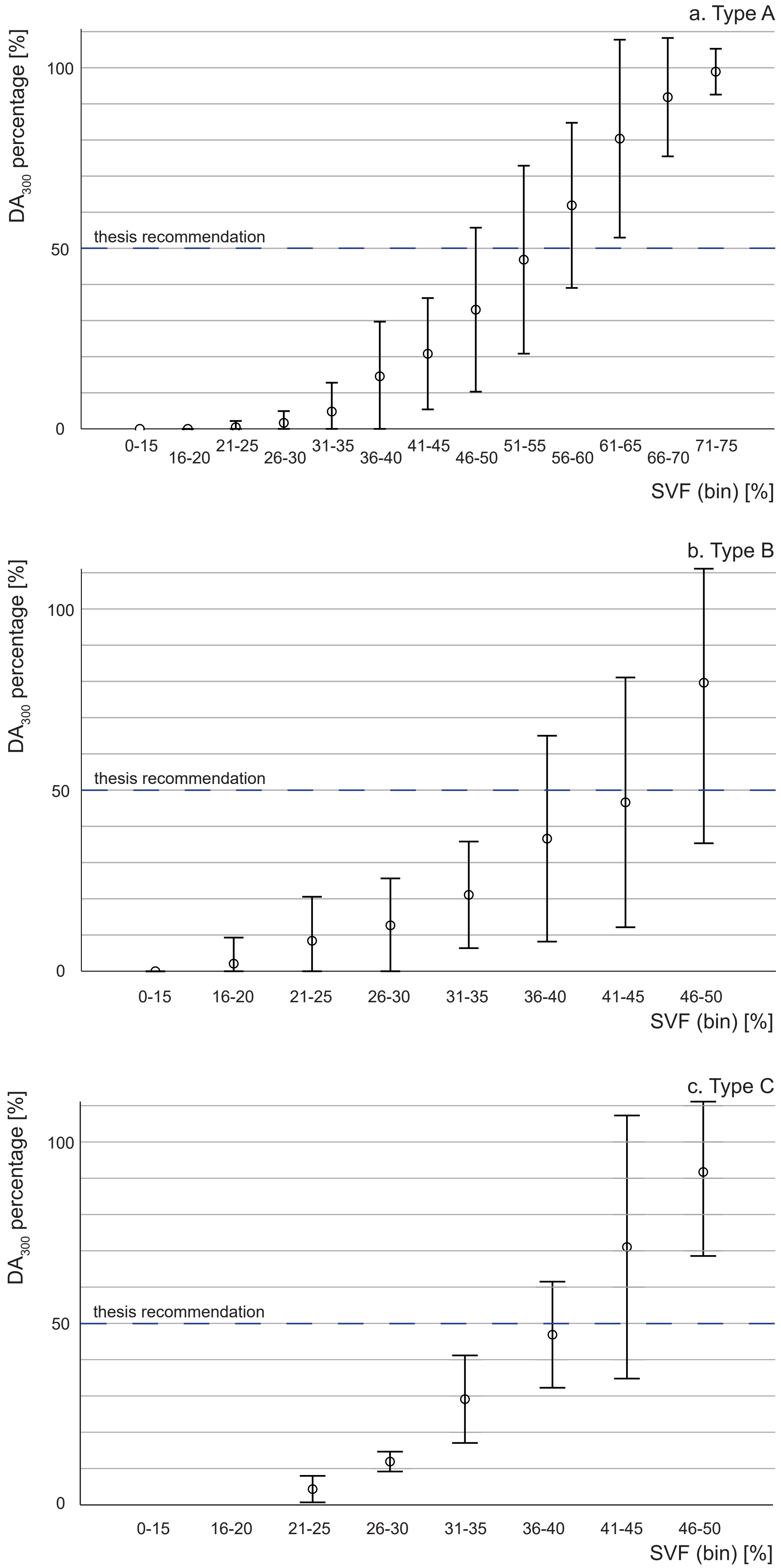


Figure 34.a-c: The mean DA_{300} percentage as a function of SVF, binned. Bin size is 5%. Error bars represent +/- 2 SD for 75% certainty (Chebychev, 1867).

dynamic TAI simulation

$DF_{2.1}$ and DA_{300} performance can be expressed as the percentage of a room that fulfils requirement. Therefore, its maximum value is 100%. However, this means that performance can hit a plateau of 100%, and no performance distinction can be made above this number (105% performance is not possible). This is required in statistical analysis later on, or if a general performance decrease needs to be determined as a function of another variable. A way to get around this limitation is by using a metric that can be expressed with continuous values and with infinite values (but still related to static and dynamic performance). Previously, for the static daylight analysis, the DF_{avg} is used as a continuous metric. For the dynamic daylight analysis, the total annual illuminance per sensor point (TAI in klxh) is used.

Ultimately, the DA_{300} performance can be tested as a function of TAI performance to see if there is a TAI threshold from which the thesis recommendation is met. An example of this comparison can be seen in Figure 35. By using this method, we can derive that for any northern facing residence, a TAI value of ca. 1600 klxh is sufficient to fulfil the thesis requirement. However, for other orientations the threshold is much higher and it is unknown how close 1600 klxh is to its theoretical maximum.

Looking at TAI per sensor point as a function of building floor in Figure 36, we can see that lower building floors generally result in lower a lower TAI performance. This is especially the case in higher density urban areas. We can also recognize that some orientations perform relatively well, such as the south-west orientation, with high TAI performance at medium building floors levels. However, expressing the TAI performance as a percentage of its theoretical maximum value will reveal how much the performance penalty actually is.

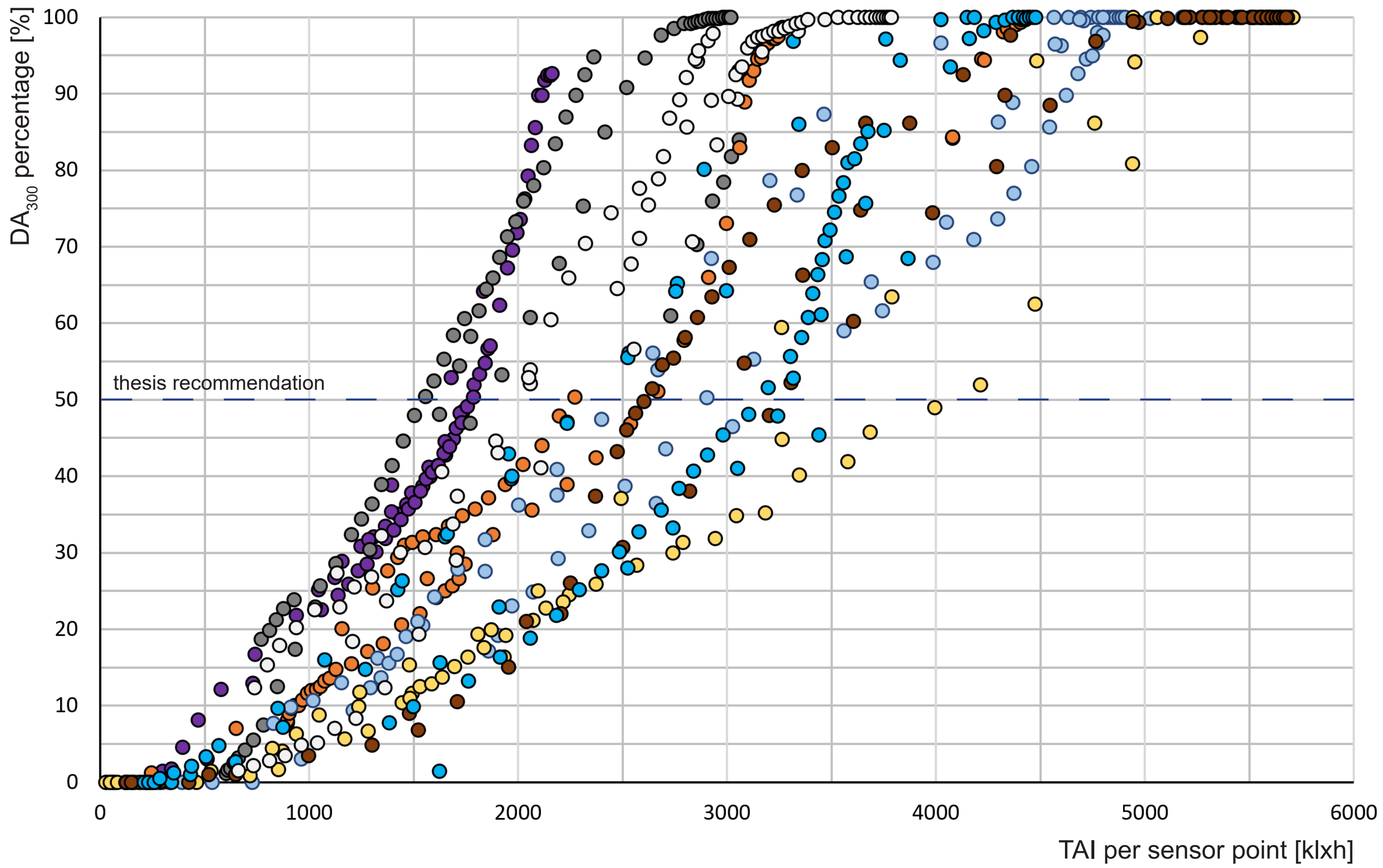


Figure 35: DA_{300} percentage as a function of total annual illuminance for all data entries.

N NE E SE S SW W NW

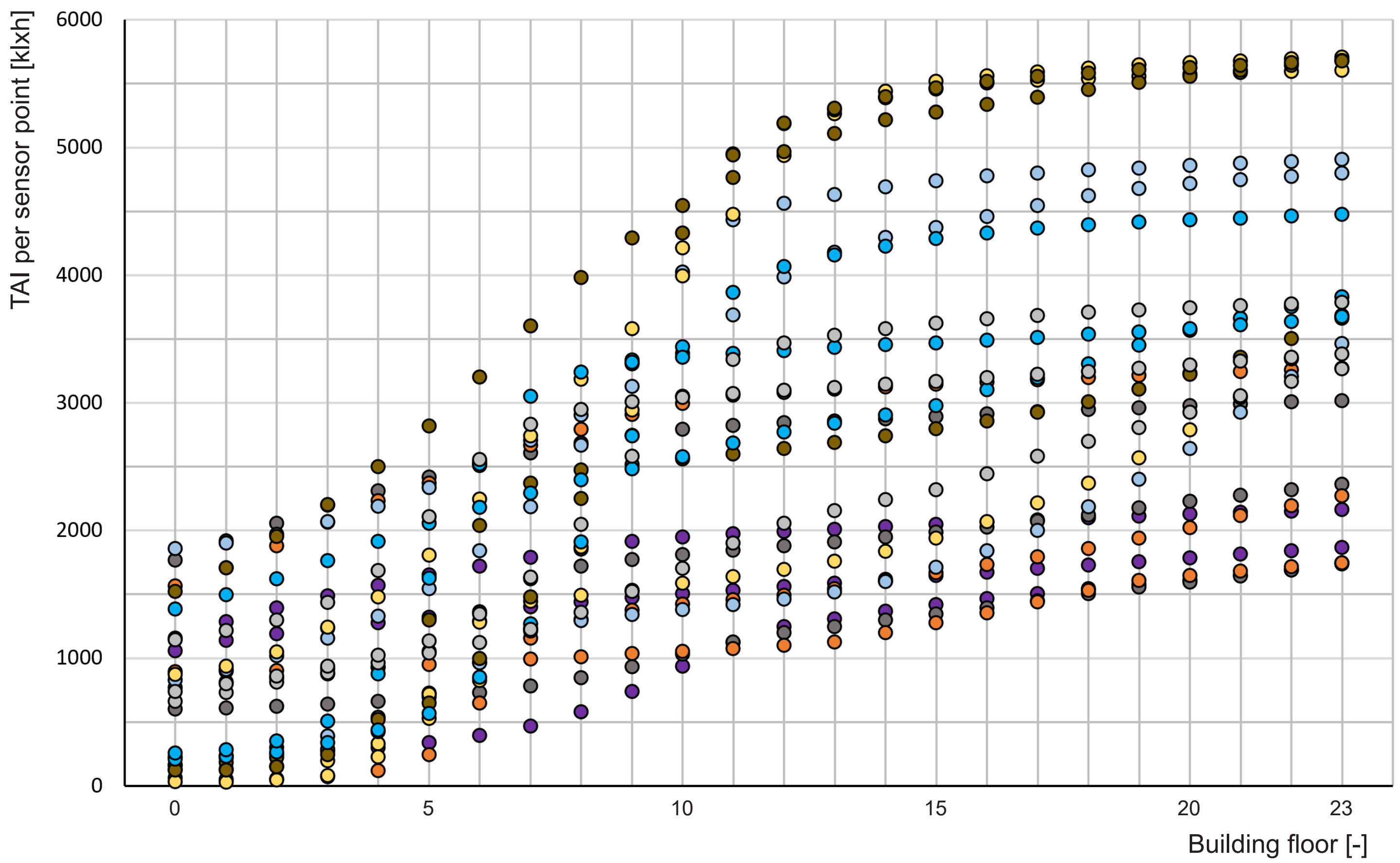


Figure 36: TAI per sensor point as a function of building floor level for the residential tower results.

N NE E SE S SW W NW

To give an answer to this question, the TAI values are normalised. For all residences, the theoretical maximum performance is simulated (without context in the simulation model). The normalised TAI performance is presented as a percentage of said maximum performance. This is plotted in Figure 37.

Looking at the DA_{300} performance as a function of normalised TAI in Figure 37, we can differentiate thresholds for different orientations to fulfil DA_{300} recommendations. Looking at the base performance of all residential types in Figure 6, it is expected that south-facing residences perform up to 60% better than a north-facing residence.

This is recognised in TAI performance (Figure 35) but does not translate over to DA_{300} performance. In fact, according to the data, the DA_{300} recommendation is almost just as easy to fulfil for NE-facing residences than it is for SE facing residences, at a normalised TAI percentage of only 44%. The hardest requirement is for the north-facing residences with 87%. In other words, with residences orientated on the north-east, performance may decrease with 60% in dynamic simulation and it would still fulfil. For north facing residences performance may only decrease with 13%.

The result that a north-east oriented residence performs better than other orientations is unexpected and raises questions to what extent the result is influenced by other factors. It is already concluded that the SVF shows a strong relation with performance in both static and dynamic simulation, hence this could explain why these discrepancies in the results appear.

In conclusion, the TAI metric is a continuous metric that is used for statistical analysis in the report as well as for descriptive statistics on estimated performance decrease as a function of various parameters (i.e. building floor, SVF and orientation). The TAI performance is correlated to DA_{300} performance but it does not indicate how close this value is to its theoretical maximum. To analyse this, the TAI performance has been normalised which revealed that a performance decrease of 13-56% is allowed to still fulfil the thesis recommendation, depending on orientation. More analysis on independent design parameters is necessary to see if they agree on these percentages.

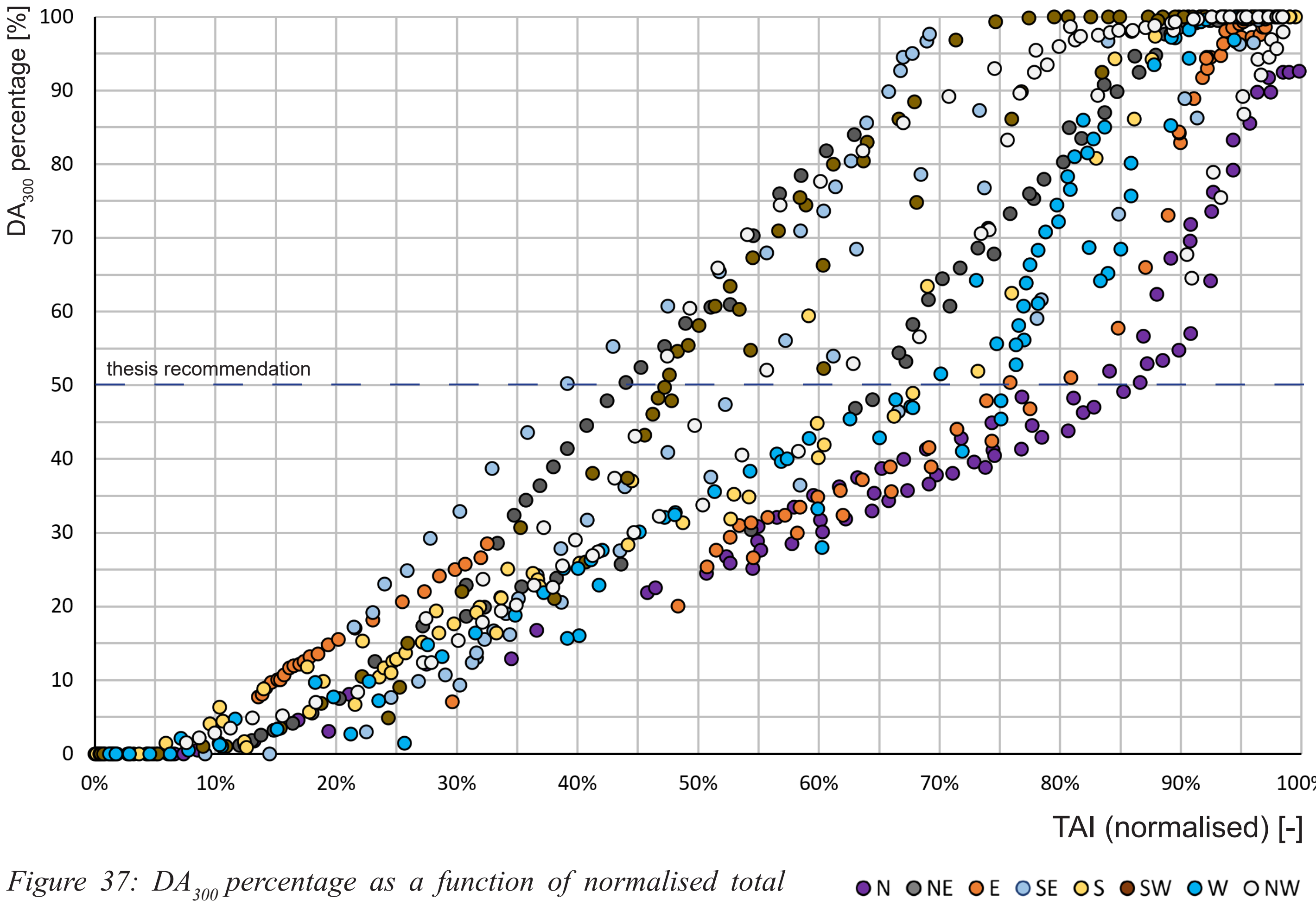


Figure 37: DA_{300} percentage as a function of normalised total annual illuminance for all data entries.

Melanopic light exposure

After analysing the photopic performance of residences in urban context, it is interesting to know the melanopic performance in residences that are considered 'adequate' according to previous assessment methodologies. The most interesting residences for melanopic performance assessment are the residences that fulfil the BBL requirement ($DF_1 \geq 50$ or $DA_{144} \geq 50$) as well as the residences that fulfil the thesis recommendation ($DF_{2.1} \geq 50$ or $DA_{300} \geq 50$). Their melanopic performance is assessed with the use of two new metrics that are introduced in this thesis: Melanopic Autonomy (MA) and melanopic Isotropy (MI). A graphical example is presented in Figure 38.

Melanopic autonomy is defined as the area percentage that has 1 or more view directions (vectors) that fulfil a requirement. For the thesis recommendation, the requirement is set at 250 $M\text{-}EDI_{D65}$. For all points on the sensor grid (1000mm spacing), four vectors are simulated, orthogonally to the rooms orientation.

Melanopic isotropy is defined as the total percentage of vectors that are melanopic autonomous. Therefore, the MI percentage is always lower than the MA percentage. The MI expresses how 'flexible' the room is for sufficient melanopic exposure. In other words, in a room with a MI percentage of 100%, you receive enough melanopic stimulus in all directions you look in.

The combination of both melanopic autonomy and isotropy is sufficient to assess the melanopic performance of any room. For both metrics, a higher percentage is more favourable. Preferably, the performance will be simulated for both equinoxes and solstices of the year to get an impression of the performance throughout the year. However, this will lead to unrealistic results because of the static sky definition inside the LARK plugin.

To explain this, we must understand that the unit for melanopic performance is simulated in melanopic-equivalent daylight illuminance, for standard illuminant D65 ($M\text{-}EDI_{D65}$). Therefore, the SPD properties of CIE standard sky D65 (2022) is used. In real life, the sky conditions vary throughout the day but in LARK it is not possible to account for this with different SPD values during simulation. Also, the sky condition cannot be defined manually so the direct normal illuminance from the weather file is always included in simulation. This leads to unrealistic performance if the point-in-time simulation is run for an actually cloudy day. To work around this problem, the melanopic assessment is done for the closest sunny day away, for both equinoxes and solstices.

To find a sunny day in the weather file, data on the recorded sky coverage is used. The 'sky cover' describes how much of the sky is covered with any object, ranging from 0.0 (completely clear) to 1.0 (overcast). Values of ≤ 0.2 are considered clear sky condition according to the American meteorology society (AMS, 2012). The closest day with an average sky cover ≤ 0.2 is chosen for this study. For the Amsterdam Schiphol weather file, these dates are the 26th of March, the 7th of June, the 29th of September and the 4th of January. The assessment is done for each hour between 08:00 and 18:00 on those days (UTC+1).

As mentioned earlier, the residences that are assessed fulfil the BBL requirement and/or the thesis recommendation for photopic daylighting. We are interested in the performance with urban context in the simulation model. The context of Rotterdam Maritime is used to perform this assessment since it is the only high-density urban area that has residences that fulfil both requirements in all four cardinal orientations.

To streamline the analysis, only residences of type B are assessed. For the cardinal orientations, the first residences that fulfils either BBL or thesis requirement is chosen as a function of building floor. An overview of the residences can be found in table 11 and 12.

Reading from tables 11 and 12, it seems that the SVF to comply to DA_{300} recommendations is nearing its maximum value. This is in accordance with earlier findings on SVF threshold values for type B residences. For residences that comply with BBL requirements, the story is different, with lower SVF values required. The required building floor is also significantly lower. Analysis is required if the photopic performance differences are also reflected in melanopic performance throughout the year.

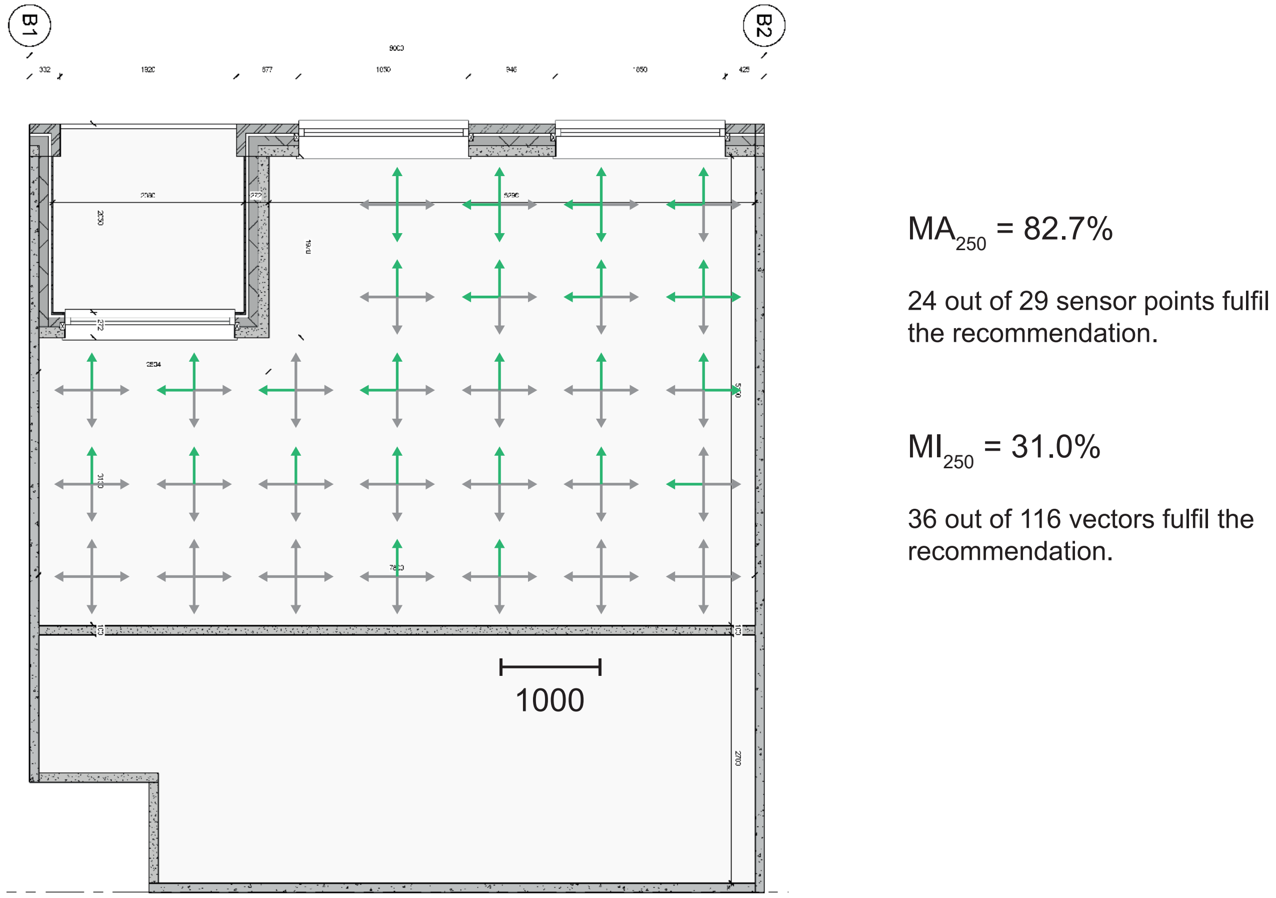


Figure 38: An example of LARK results plotted on the floor plan of a type B residence, as used in this thesis. Sensor points are 1000mm spaced, 500mm offset from the wall. Vectors with sufficient melanopic exposure are filled green. Data for Figure purpose only (not actual data). Own source.

orientation	floor level	sky view factor	DA_{300} percentage	$DF_{2.1}$ percentage
N	20	48.5	50.4	25.9
E	23	47.5	50.4	23.2
S	23	38.0	45.8	21.7
W	9	38.3	52.8	21.3

table 11: The performance of residences that fulfil the thesis recommendations (with the exception of the south facing residence). These will be used for melanopic assessment.

orientation	floor level	sky view factor	DA_{144} percentage	DF_1 percentage
N	0	38.6	56.2	30.5
E	6	32.0	70.8	41.0
S	12	22.7	50.0	17.1
W	7	31.2	62.3	33.6

table 12: The performance of residences that fulfil the BBL requirements. These will be used for melanopic assessment.

The results for the residences that fulfil the thesis requirement of $DA_{300}\geq50$ are positive. Generally speaking, all orientations achieve an MA_{250} value of 100% during morning hours and they maintain their performance throughout the day. The results for the 4 assessed days can be seen in Figure 39a to 39d. During spring and autumn equinox, the MA performance is lower in the early morning between 07:00 and 08:00 (sunrise at 07:30 (KNMI, 2022)) but quickly increases to MA_{250}=100%. However, around winter solstice, MA_{250} performance is insufficient in the morning and at the end of the afternoon. This is because sun rises at only 08:48 (too late) and sun sets at 16:41 (too early).

The results for the residences that fulfil the BBL requirement of DA_{144} are a mix of positive and negative. These residences are assessed for the same melanopic requirement of MA_{250}. Looking at Figures 40a to 40d, the west and north facing residences keep up with the performance of the better daylit residence on the top floors. The performance of the south facing residence is noticeably worse than its floor-23 counterpart. With the exception of the early morning and late afternoon, performance can keep up with the better daylit residence on the top floor. The east facing residence is performing significantly worse compared to its DA_{300} counterpart. Large obstructions in this orientation is expected to be the explanation for this performance decrease. On all days, performance is mediocre around midday with peak performance in the afternoon due to external building reflectances. As expected for an east facing facade, performance in the morning is sufficient but yet never as adequate as other orientations.

In conclusion, for most residences that fulfil DA_{144} requirement in urban context it is inevitable that additional artificial lighting is necessary to maintain enough melanopic light exposure throughout the year. This is especially the case in wintertime but it also applies for the south and east facing facades during other times of the year.
For the residences that fulfil the thesis recommendation in urban context, performance is sufficient for most of the year and throughout the day. With the exception of the east facing residence late in the afternoon, all residences show 100% melanopic autonomy, meaning that the these residences can be considered healthy in terms of melanopic stimulus. Artificial lighting is still necessary in wintertime and in early mornings but this would be the case for all buildings in the Netherlands.

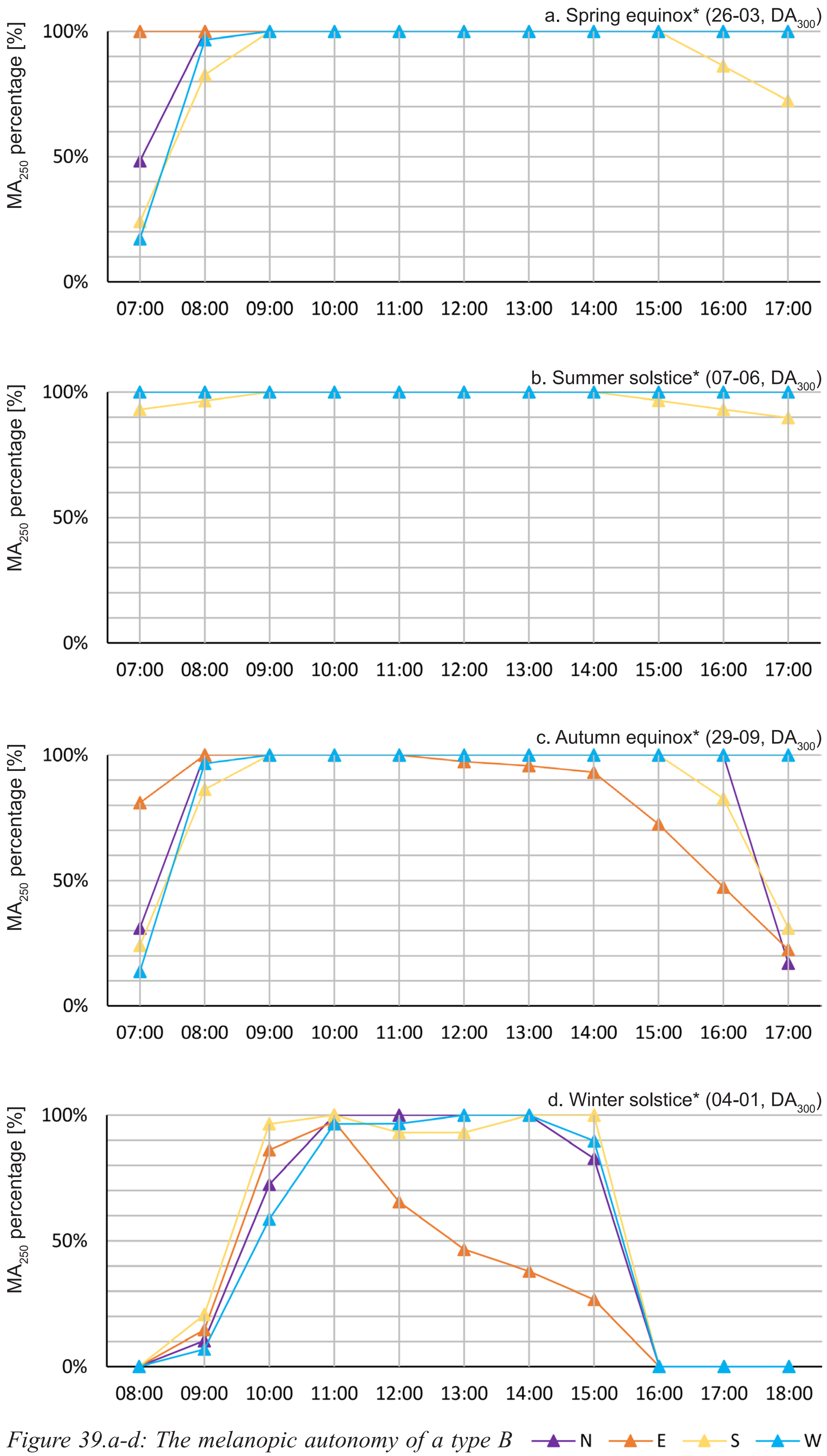


Figure 39.a-d: The melanopic autonomy of a type B residence that fulfils DA_{300}=50%. The four Figures are sunny days that are closest to both equinoxes and solstices. Times are in UTC+1 (no summertime).

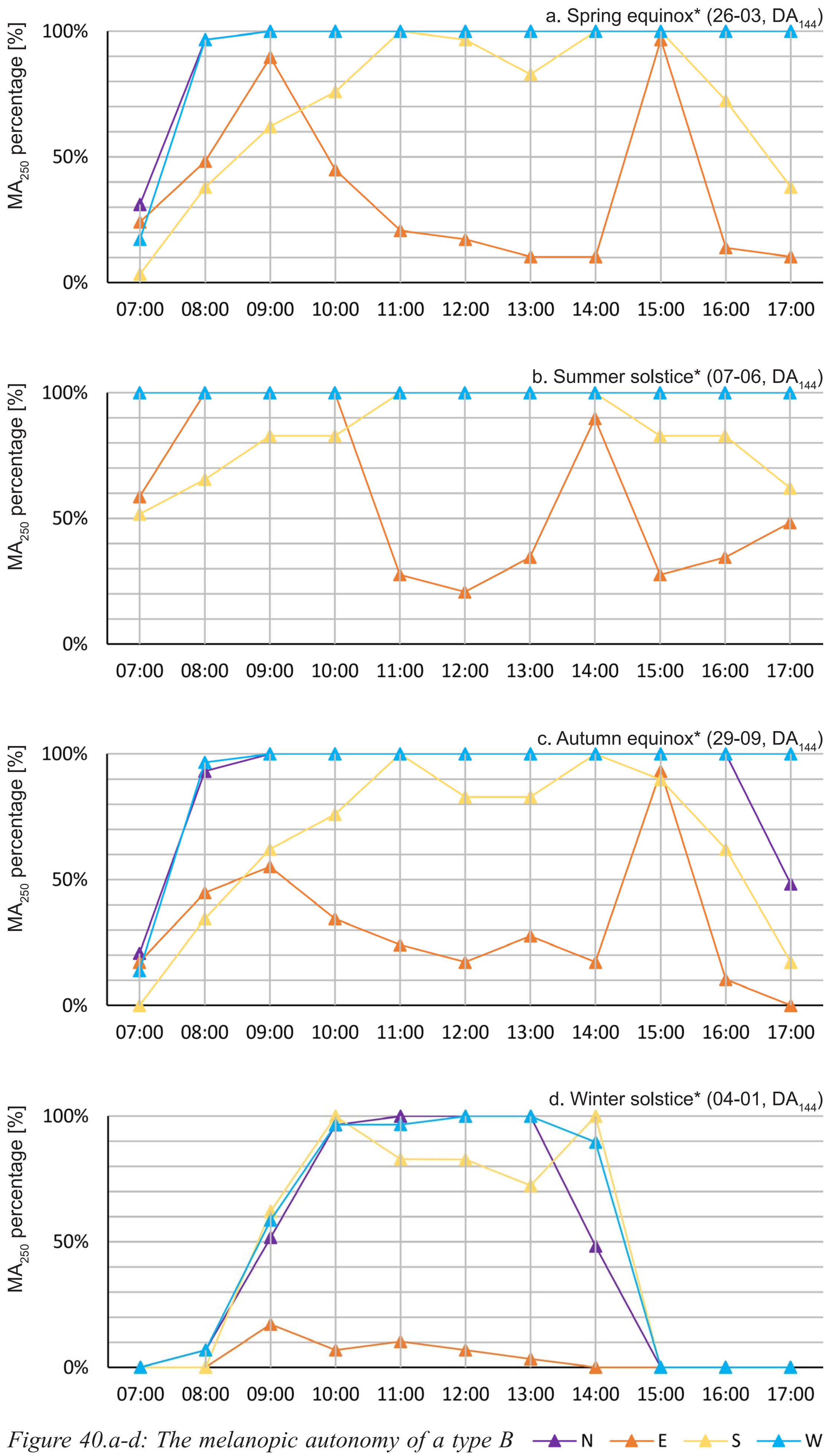


Figure 40.a-d: The melanopic autonomy of a type B residence that fulfils DA_{144}= 50%. The four Figures are sunny days that are closest to both equinoxes and solstices. Times are in UTC+1 (no summertime).

The melanopic isotropy is an expression of the total percentage of vectors that fulfil the thesis requirement (M-EDI_{D65} ≥ 250). If a residence performs 100% in both metrics, it means that there is no risk for insufficient melanopic exposure: every view direction (even looking at an interior wall) results in sufficient non-visual stimulus according to the literature. If the MI performance decreases, the risk of a resident not receiving sufficient stimulus increases. More often than not, the MI performance is significantly lower than the MA performance, meaning that view direction is important to consider.

For residences that fulfil the thesis requirement of DA_{300}, we concluded that MA performance is sufficient for most of the year. However, the MI performance in Figures 41a to 41d shows that west and north facing residences are more selective in view direction. The west facing residence is especially performing worse until 15:00, from which the isotropy increases beyond the performance of the other residences. The north facing residence performs better throughout the year, being less selective for view direction as a result of a higher SVF (table 11). The south facing residence is performing the best on MI, showing a more consistent performance than other orientations (especially around winter solstice) but worse in early mornings. Lastly, the east facing residence performs well in the early mornings but performance drops towards the end of the afternoon.

The melanopic isotropy of the residences that fulfil BBL requirement takes a significant hit in performance compared to the residences that fulfil thesis requirements. This can be seen in Figures 42a to 42d. The performance differences per orientations are enlarged compared to the MA performance. The north and south facing residences perform relatively consistently throughout the day, with the northern residence performing better during summer solstice and the southern residence performing better on all other days. The east facing residence only performs well during morning hours but the performance completely drops off at the end of the morning. For the west facing residence, performance is similar to that of its DA_{300} counterpart, explained by the similar floor level of both residences (building floor 7 & 9). These residences lack MI performance in the morning hours but performs generally better than the rest in the afternoon.

*) Dates are representative for the equinoxes and solstices

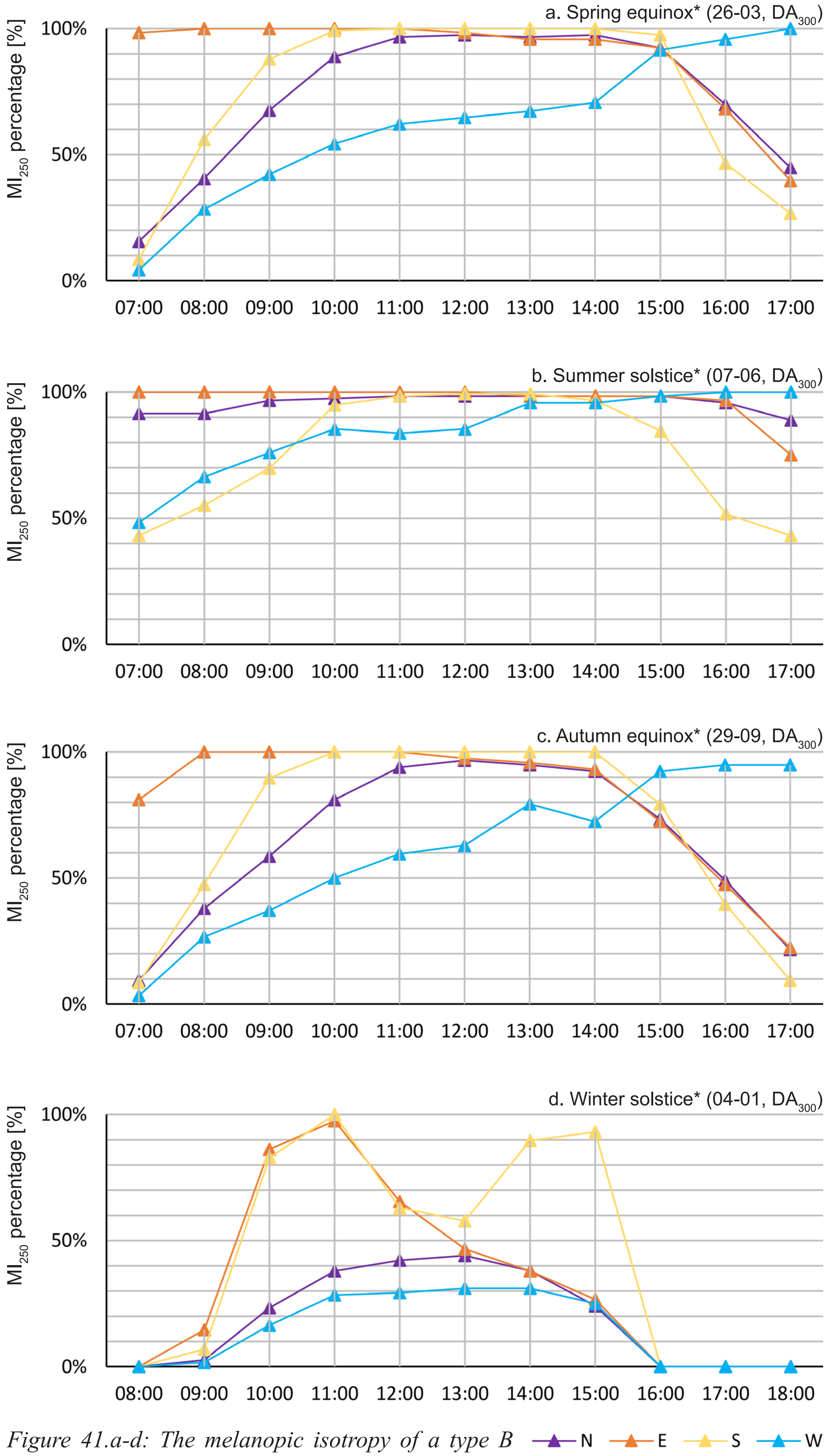


Figure 41.a-d: The melanopic isotropy of a type B residence that fulfils DA_{300}=50%. The four Figures are sunny days that are closest to both equinoxes and solstices. Times are in UTC+1 (no summertime).

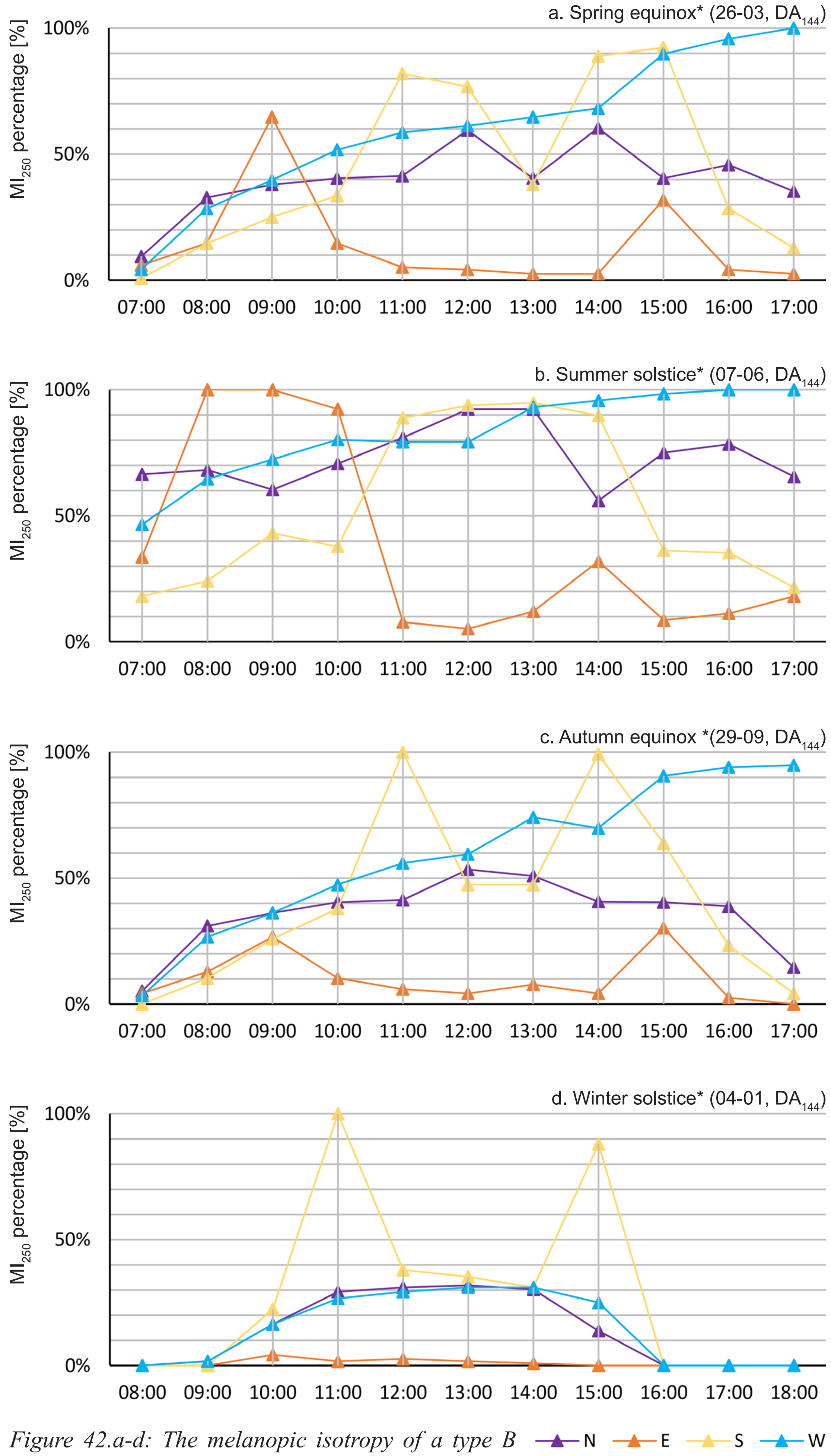


Figure 42.a-d: The melanopic isotropy of a type B residence that fulfils DA_{144}= 50%. The four Figures are sunny days that are closest to both equinoxes and solstices. Times are in UTC+1 (no summertime).

In conclusion, the residences that fulfil the thesis recommendation of DA_{300}≥50 generally perform well in melanopic autonomy (MA) and melanopic isotropy (MI). For the east facing residence, the MI performance is on the low side which is arguably insufficient in some periods of the year. For other orientations, there is little to no risk for insufficient melanopic stimulus throughout the year. Extra artificial daylighting is necessary in wintertime and early mornings but this recommendation can be made for all occupied spaces in the Netherlands.

The conclusion is different for residences that fulfil the BBL requirement of DA_{144}≥ 50. They all need additional artificial lighting at some point during the day, at some point in the year. Performance of the east facing residence drops off the worst, followed by the south facing residence. According to the MI data, the north and south facing residences are more flexible in positioning in order to receive sufficient non-visual stimulus throughout the day.

A limitation and remark of this method of assessment is that the presented results are gathered in simulations on sunny days under CIE standard sky D65 conditions. Therefore, the results of this thesis give an indication of the 'best case scenario', and not a more typical result. It is recommended that additional research is necessary to assess performance with cloudy and overcast sky conditions. However, melanopic autonomy and melanopic isotropy seem suitable metrics to assess the non-visual exposure throughout a period of time.

Urban characteristics and daylighting performance

At this stage of the thesis, the photopic performance of the assessed residences is known, its behaviour in relation to different design parameters and an impression of the melanopic performance is formed. All the relations and correlations that were found were on a relatively small scale, only addressing one parameter at a time. On a larger scale, more interesting is if there are any urban density indicators that correlate with daylighting performance. To investigate this, the research takes a closer look at the properties of the assessed urban areas.

Reflectance properties: building reflectance

For all the assessed locations, the reflection value of the surrounding buildings is calculated for each building individually and used in the daylighting simulation model. The reflectance differences are not large but they do affect daylighting performance in the simulations and introduce a possible error compared to the real world situation. To analyse the effect of the thesis methodology on the simulation results, a sensitivity analysis is done with different building reflectance values using real world geometry.

Five different reflectance values are tested for their performance in static and dynamic daylight simulation. These values are applied to all buildings collectively, so no other building characteristics are taken into account. The values range from 10% to 90% with increments of 20%.

Worth bearing in mind is that the reflectance of exterior materials not often exceeds 50% (e.g. white brick) and that the most reflective glazing systems do not reflect more than 40% of light (Pilkington, 2022). Using these numbers to calculate an example weighted average reflectance, the maximum building reflectance is expected to be only ca. 45% in combination with a WWR of 0.5. Therefore, 70% and 90% building reflectance are hypothetical values that are used to enlarge the differences in simulation performance.

The simulation is done for three building floors in Amsterdam context. The assessment is done for the ground floor, the 10th floor and the top (23rd) floor. All eight residences are simulated and the results have been normalised to exclude the impact of orientation and residential type (hence orientation is only an indicator of the residence location in the residential building). The lowest building reflectance value (10%) is the reference performance and indexed as 100%.

Looking at the static simulation results in Figures 43a to 43c, there is little to no performance change for different building reflectances. The largest change of performance is +/- 3% on the ground floor but this is within margin of error of the simulation itself (due to small fluctuations when an identical simulation is run multiple times). For the top floor, the fluctuation is only +/- 1% because the fraction of daylight received via other building decreases for higher building floors.

In Figures 43d to 43f, an increase in building reflectance has a drastic effect on dynamic performance. The top floor sees an increase of 150% in TAI performance for residences that are obstructed by other buildings (N, NE, NW). The highest performance increase for the 10th and ground floor are also for residences that are heavily obstructed. This is allegedly explained because these residences do not receive much direct sunlight, therefore the fraction of daylight received via other buildings is greater. This makes the reflectance value of other building more important for those residences.

Looking at the reflectance range we can expect in the real world (10-50%), the differences are significant in dynamic simulation but more so for residences that are obstructed by other buildings. The increase in performance between 10% and 50% reflectance is ca. 10-65%, depending on the orientation and obstruction. However, increasing external reflectance values is not always a viable design strategy to increase daylighting performance. Especially considering that the Amsterdam context is one of the most dense urban patches of the Netherlands, the results may be much less pronounced, especially in less dense urban areas.

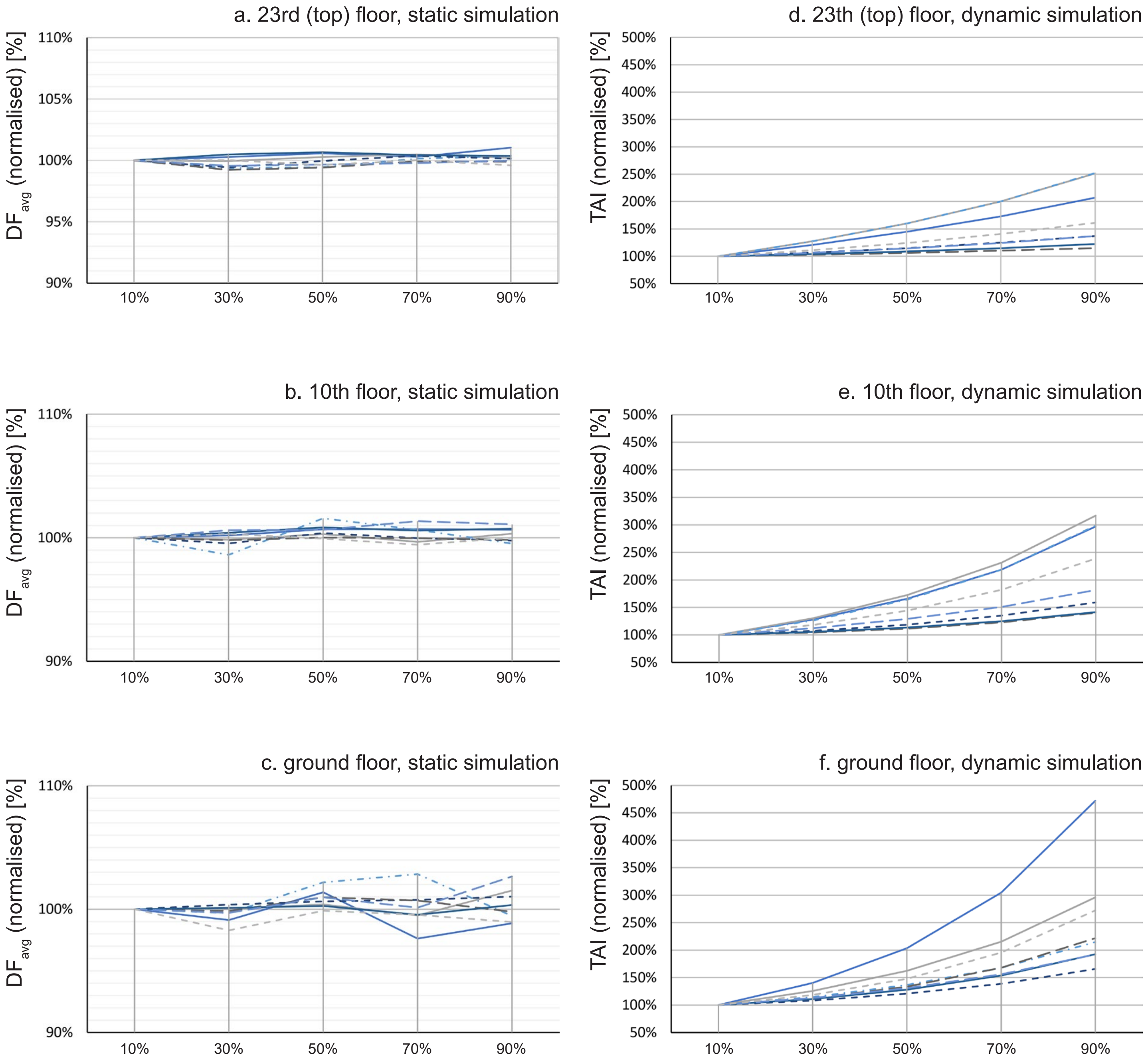


Figure 43.a-f: ***Building reflectance.*** *The normalised performance increase for different building reflectance values. 10% building reflectance is indexed as 100. For static performance, DF_{avg} is used for comparison. For dynamic performance, TAI is used for comparison.*

Reflectance properties: ground reflectance
Ground reflectance properties are also tested for their impact on daylighting performance for the same reason as for the building reflectance, using the same methodology. The simulation setup is identical. Realistic ground reflectance values are ranging from 5% to 30%, depending on the roughness of the surface and material properties. Hence the results for 50-90% ground reflectance are hypothetical simulation results and considered not possible in the real world. For this simulation, patches of greenery and bodies of water are disregarded and a uniform ground surface is modelled.

In static simulation, only for the ground floor an increase in performance is recorded, as can be seen in Figures 44a to 44c. A reflectance increase from 10% to 90% results in a performance increase of up to 14% depending on the orientation. The south and north facing residence both have a low SVF, hence the fraction of daylight they receive via the ground is larger, explaining why they are more affected. For the 10th and 23rd floor, the performance fluctuation can be caused by the standard error that can be expected when an identical simulation is ran multiple times.

Striking is that in dynamic simulation, an increase in ground reflectance results in a significant increase in performance. This can be clearly seen in Figures 44d to 44f. For the top floor, the increase in performance is relatively small with an increase of 4% in the realistic reflectance range (5-30%). For the ground floor, the increase is more significant and performance can be up to 30% better with reflectance values in the higher bound of the realistic range. The performance increase between 10% and 30% ground reflectance is in the same order of magnitude as increasing the transmission a glazing system by ca. 10%, making it an effective design strategy.

In conclusion, increasing the ground reflectance is effective for residences close to ground floor but has little to no effect on residences that are higher up. Considering a realistic range of ground reflectance, the performance differences are small but measurable. Even though performance can be doubled for some orientations at ground floor, it is not expected that it is sufficient to increase daylighting performance to adequate levels according to the thesis requirements. Hence other mitigation strategies need to be employed as well to increase overall daylighting performance.

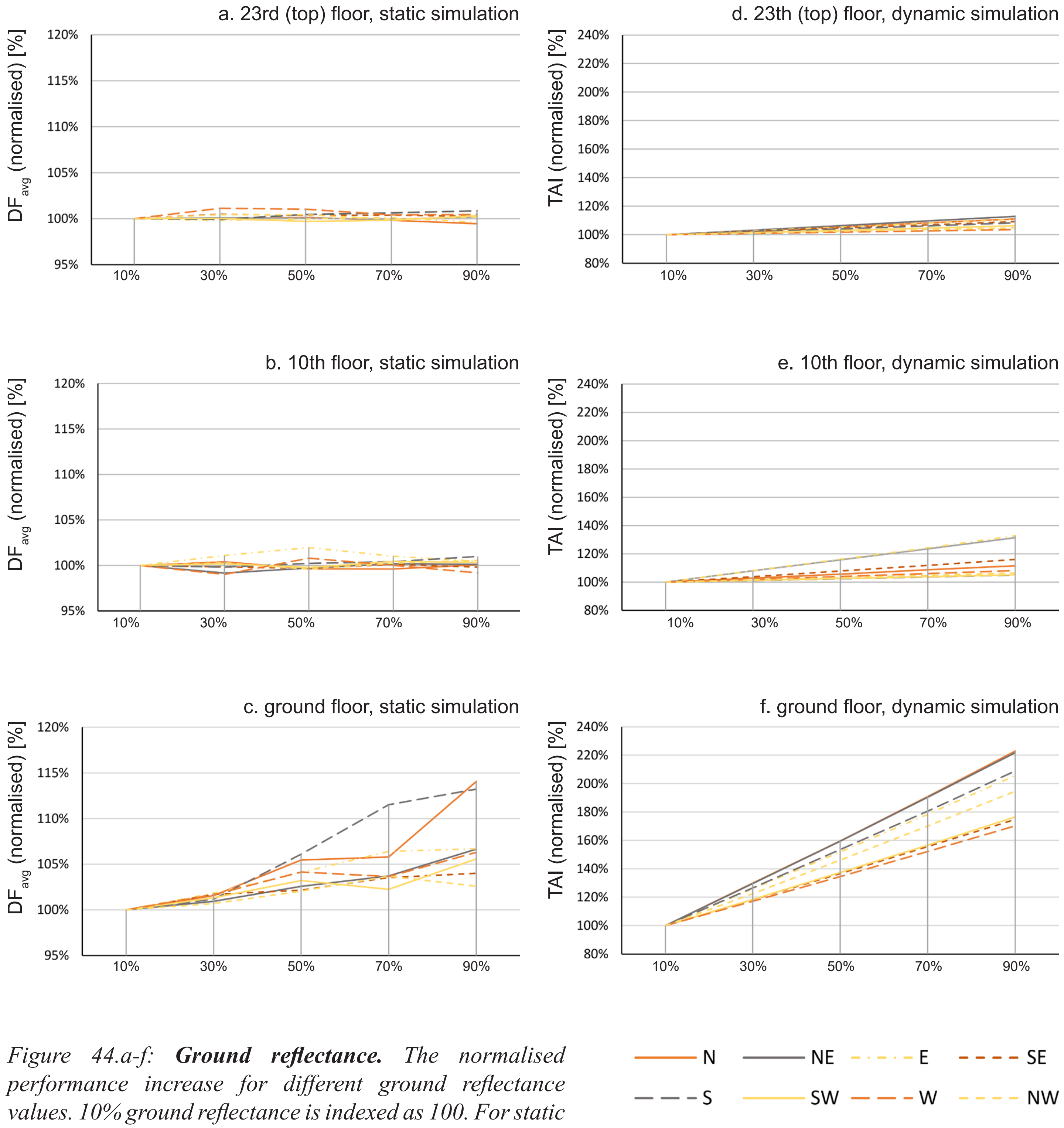


Figure 44.a-f: ***Ground reflectance.*** *The normalised performance increase for different ground reflectance values. 10% ground reflectance is indexed as 100. For static performance,* DF_{avg} *is used for comparison. For dynamic performance, TAI is used for comparison.*

urban density characteristics

One of the main objectives of this thesis is to see if there is a correlation between urban density and daylighting performance. If possible, this thesis is interested in recommendations for urban scale mitigation strategies. A possible correlation between urban density indicators and daylighting performance may lead to an advice for (urban) designers to keep in mind daylighting performance above or under a certain density threshold. To investigate this, daylighting performance for six different urban areas is simulated, all with different urban densities. By doing this, we can analyse how strong the relation between FSI, GSI, OSR and daylighting performance is.

In Figure 45, the static and dynamic performance as a function of the six cities is shown in a boxplot. The highest density areas are easily recognized by their worse performance numbers compared to medium-density cities. Amsterdam, Rotterdam Maritime and Utrecht seem to have similar mean performance in dynamic simulation: suggesting that these areas have highest density of the six locations. This can be confirmed by reading the density values from Figure 10.

Furthermore, we can see the spread of results is large for the 50th percentile results. This denotes that multiple aspects can cause the performance differences and not only urban density. Therefore, especially in dynamic simulation the spread is large due to different orientations.

This is recognized in the mean performance being on the higher or lower end of the 50th percentile performance. In high-density urban areas, the mean tends to be towards the lower end of the spread. In medium-density urban areas, the mean performance is towards the higher end of the 50th percentile spread.

Up until now, the hypothesis is that urban density is indeed of influence on daylighting performance. To confirm the suspicion that urban density influences the daylighting performance, inferential statistics are used to see if the mean performance values of the cities are significantly divergent from eachother. To get to valid results, only continuous metrics can be used, hence this analysis is done with the DF_{avg} metric to represent static performance and TAI per sensor point for dynamic performance. To remove any result bias due to orientation differences, the results are normalised as a percentage of their maximum performance in a situation without any urban context. As a control, the mean normalised performance is shown for the same building without any urban context.

First, the mean performance is assessed for the walk-up apartments in Delft, Utrecht and Rotterdam North. In Figure 46 we can see that the urban environment has an impact on static simulation performance, especially so for Utrecht. In Utrecht, which is considered a high-density urban area, the mean performance is only 15-40% for the first three floors. Rotterdam North and Delft perform much better for the lowest floors with a performance of 60-85% which can be attributed to different (more favourable) urban density characteristics.

In the dynamic simulation, much of the same trend can be seen in Figure 47. Utrecht performs worse for ground floor but increases to the performance of Delft and Rotterdam North. For walk-up apartments, there is still a performance penalty due to the urban environment of at least 30% for the first three floors but much more for Utrecht.

Interestingly enough, the performance in static and dynamic simulation is up to 80% of the maximum performance from the fourth floor and upwards. Despite a higher density, this also applies to the Utrecht location. It seems that the difference in extreme performance (maximum vs minimum) is larger in higher density urban areas. The rate of change per building floor in much steeper for Utrecht, than it is for Delft or Rotterdam North. The uniformity of building heights in Utrecht might by causing this (almost all buildings are ca. 4 building floors, 12m (AHN, 2019)) but it is also a possibility that certain density characteristics can be of influence.

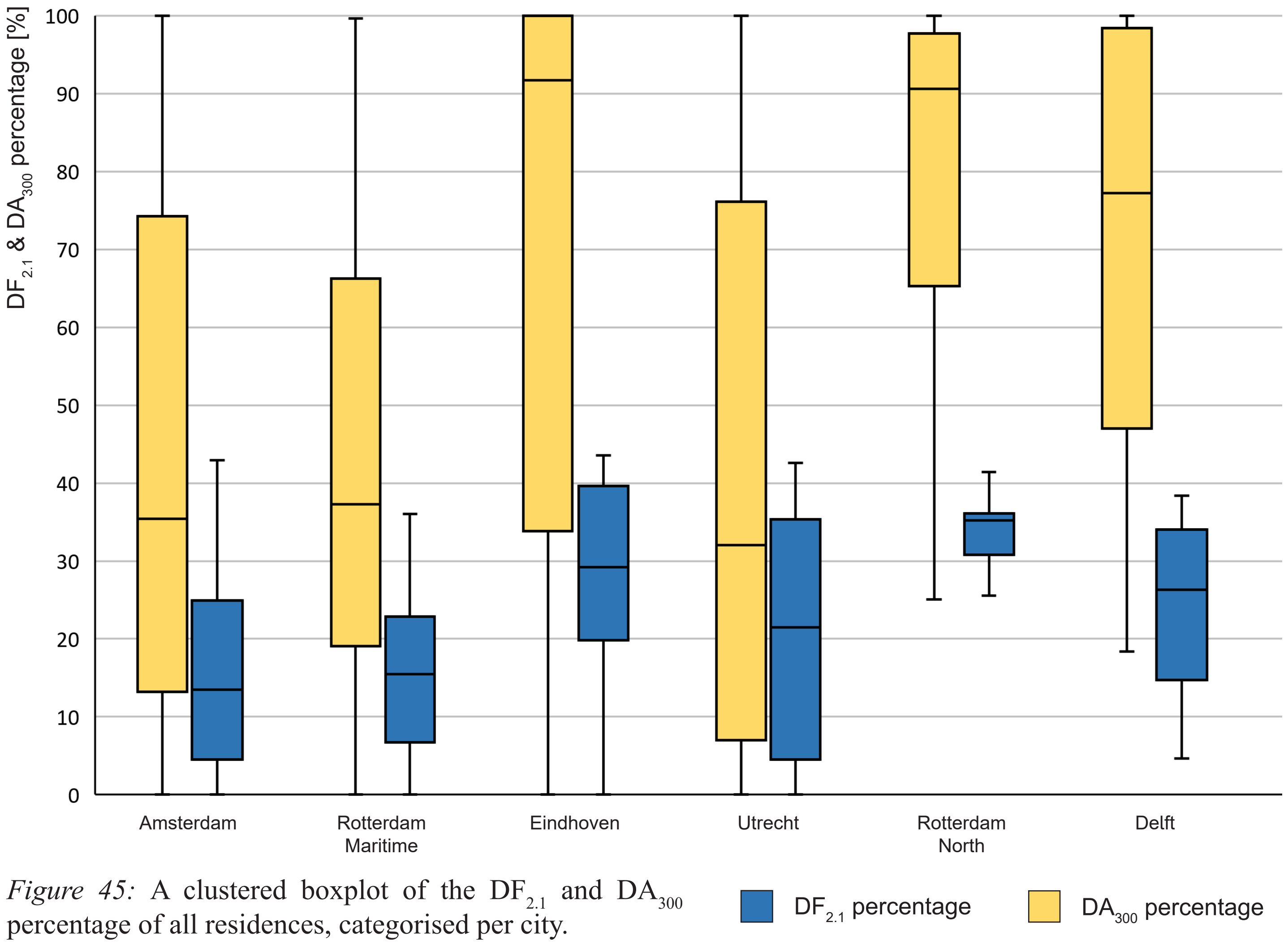


Figure 45: A clustered boxplot of the $DF_{2.1}$ and DA_{300} percentage of all residences, categorised per city.

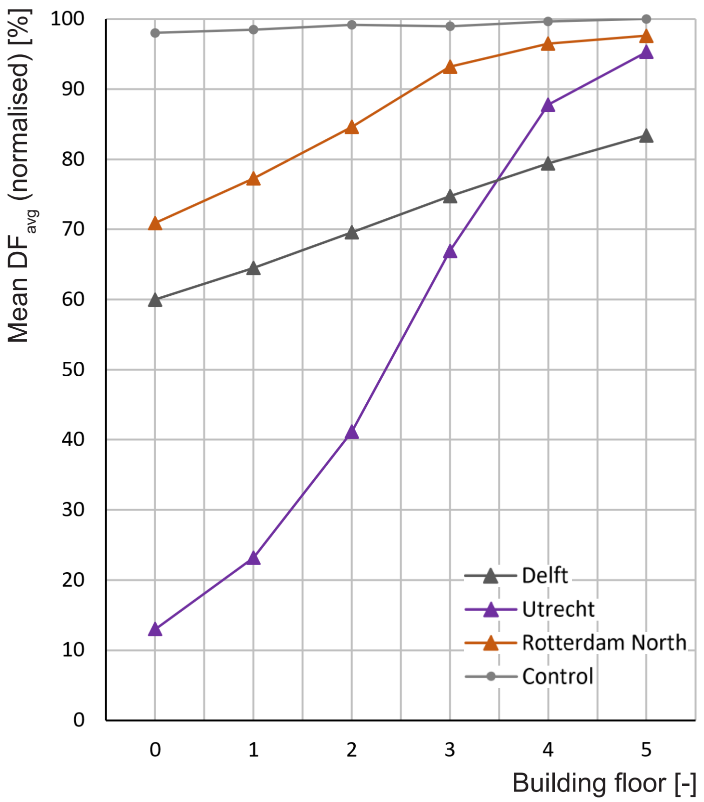


Figure 46: Static performance as a function of building floor, for three cities with walk-up apartments. On the Y-axis is the mean DF_{avg}, normalised to the maximum performance with no context.

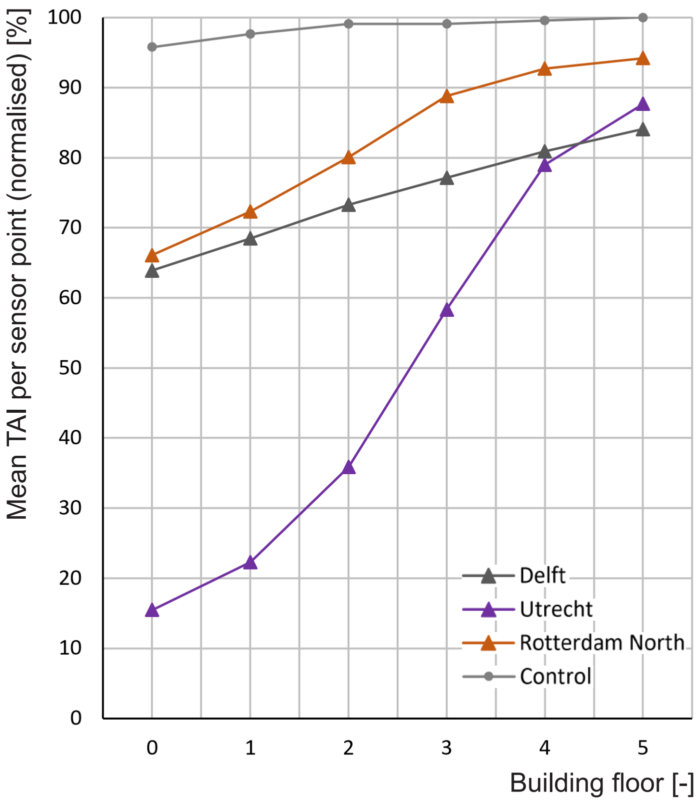


Figure 47: Dynamic performance as a function of building floor, for three cities with walk-up apartments. On the Y-axis is the mean TAI performance per sensor point, normalised to the maximum performance with no context.

Similar to the walk-up apartment results, the same analysis is done for the residential tower In Amsterdam, Rotterdam Maritime and Eindhoven context. As a control, the performance of an identical building with no context is simulated and plotted in Figures 48 and 49.

In static simulation, interesting results are yielded if the mean performance is plotted as a function of building floor (Figure 48). In terms of ranked performance per building floor, Eindhoven performs the best and Amsterdam performs the worst. What stands out is the close performance in Amsterdam and Rotterdam Maritime for floors 0-5, which then diverges until building floor 11. From building 12 and upwards, the Eindhoven location performance excellent, performing almost as good as the control building. Amsterdam and Rotterdam Maritime remain to perform similar to each other, which is attributed to similar urban density characteristics.

Looking at the simulation results in dynamic simulation (Figure 49), the performance trend is much the same but the ranked performance per building floor is different for floors 6-10. These are the building floors where Rotterdam Maritime sees a higher rate of change in performance than Amsterdam (similar to Eindhoven between floors 7-11). This is likely to be caused by the uniform height of adjacent buildings in Rotterdam (ca. 8 floors, 24m) and Eindhoven (ca. 11 floors, 34m) (AHN, 2019), which also happens to be the height from which the rate of change is stable. Important to know that this height is not the average building height in the areas. The uniformity of the surrounding context is absent in Amsterdam, where many of the buildings are stepped in height and no 'podium' is in the urban environment. This makes for a smoother performance increase as a function of building floor which can be easily recognized in both Figures 48 and 49.

For all building floors in static and dynamic simulation, the residential tower in Eindhoven context performs better. This can be attributed to urban density characteristics but the differences in performance seems to be especially present in higher building floors, with a higher 'performance ceiling' in Eindhoven. The performance ceiling of ca. 80-100% is also reached in all medium-density areas, albeit at much lower building floors. The absence of other tall buildings in the direct surroundings is allowing the performance ceiling to be as high as 95% in some cases.

In conclusion, it looks like urban density indicators are directing the performance ceiling of the assessed residences, with high-density values having a negative impact on the maximum mean performance. The rate of change in performance seems to be high in dense urban areas with uniform context height (Utrecht, Eindhoven, Rotterdam Maritime) and the performance ceiling seems to be reached quickly when reaching the average 'podium' height. The absence of large tower buildings (medium-density areas + Eindhoven) seems to benefit daylighting performance and impacts Amsterdam and Rotterdam Maritime adversely. This leads to the conclusion of a probable correlation between urban density and daylighting performance but not a causation.

urban density indicators

Concluding from the results from the urban density characteristics analysis, it is clear that height uniformity of the urban context can be an indicator at which building floor the performance ceiling is reached. Urban density indicators on the other hand are likely to cause the 'height' of the performance ceiling. To test this, statistical analysis is done for the correlation between urban density indicators and daylighting performance.

Based on Figures 30-31-33, it is expected that the performance of lower building floors is closer together, resulting in a weaker correlation. Therefore, the lower building floors are analysed separately from higher building floors. To see if the performance ceiling is correlated with urban density indicators, similar analysis is done for high building floors. The split is made at building floor 10, which is the average of the uniform building height in Eindhoven (11) and Rotterdam Maritime (8), rounded up.

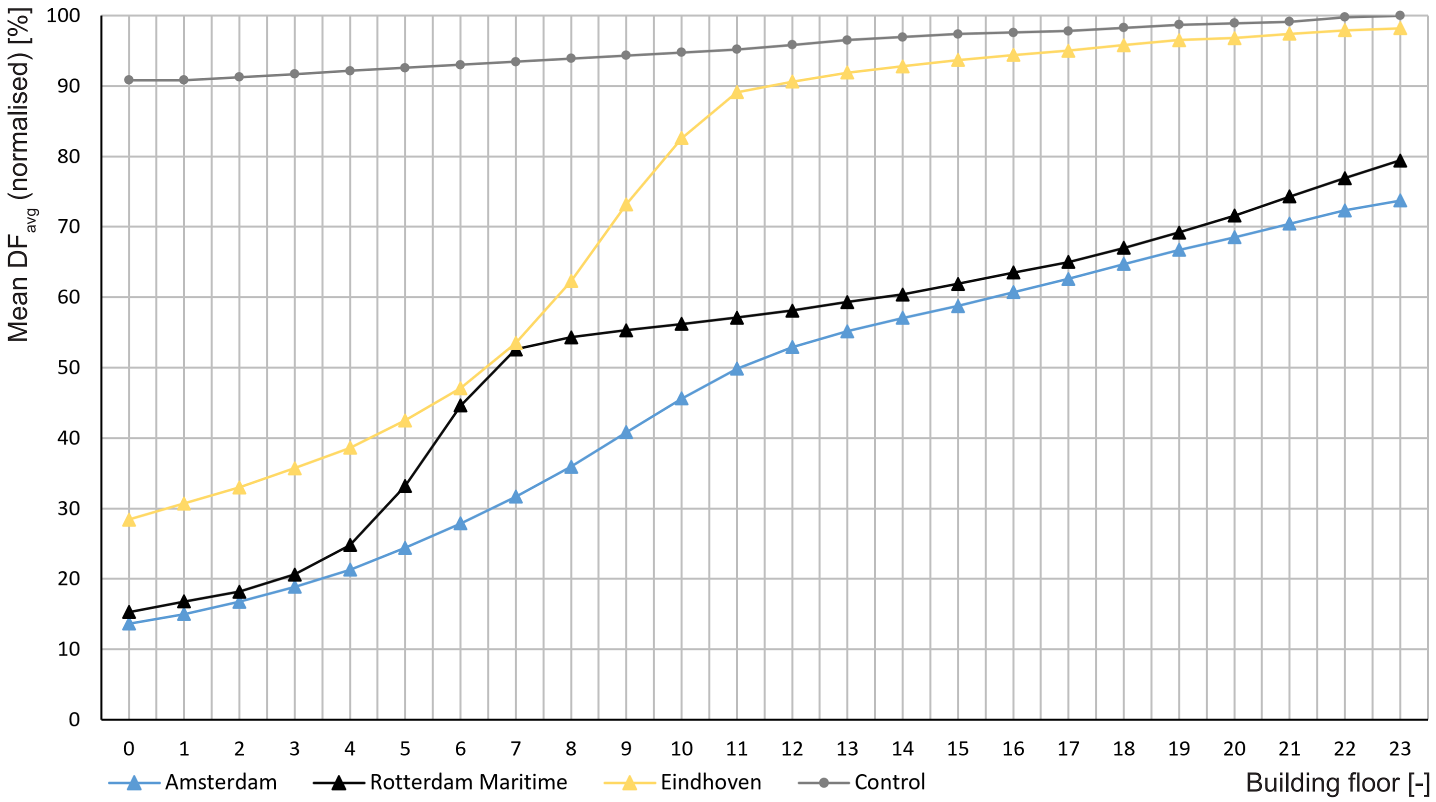


Figure 48: Static performance as a function of building floor, for three cities with the residential tower simulated. On the Y-axis is the mean DF_{avg}, normalised to the maximum performance with no context.

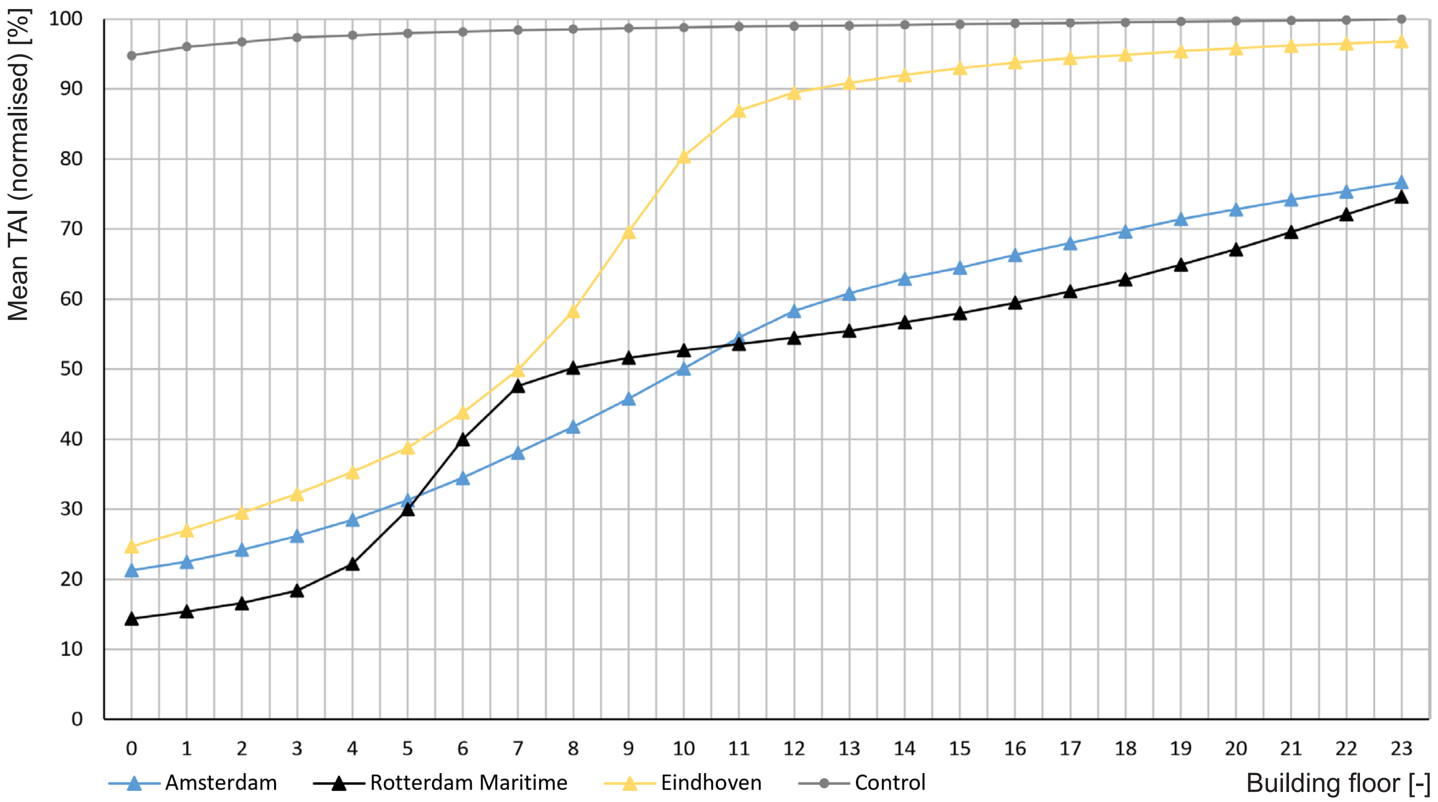


Figure 49: Dynamic performance as a function of building floor, for three cities with the residential tower simulated. On the Y-axis is the mean TAI performance per sensor point, normalised to the maximum performance with no context.

First, we are interested to see if the differences in mean performance are significantly different for every city. To test this, non-parametric statistical analysis is performed (independent-samples median test & Kruskal-Wallis H test). The tests are done for the FSI, GSI and OSR density indicators. The test has to be non-parametric since the simulation results are not normally distributed. The different cities represent independent samples in the test (n=6) and the normalised static/dynamic performance is the dependent (continuous) variable.

To start off with, an independent-samples median test is performed. It answers the question if two or more median values are significantly different compared to each other. It does so by comparing the grand median of all samples with the median of multiple independent values (the urban density of the 6 cities). In addition, it also tells us if there are two or more homogeneous subsets that have comparable mean values (IBM, 2020).However, this test does not conclude on any pattern in the results: it just shows us if the medians are significantly different.

A second test is the Kruskal-Wallis H test (known as the one-way ANOVA on ranks) and it is used to test on significant differences in the result distribution of two or more groups (Laerd statistics, n.d.). It ranks all the static/dynamic performance results and tests if it correlates with the expected rank based on FSI/GSI/OSR rank.

As with all statistical test, a null-hypothesis needs to be formulated for a correct interpretation of results. For the independent-samples median test, the null-hypothesis is that the normalised performance is similar for all the density values. The null-hypothesis for the independent-samples Kruskal-Wallis H test is that the distribution of normalised performance is similar for all density values. This test has been done for the FSI, GSI and OSR. The results of the significance are shown in table 13. A low significance means the null-hypothesis should be rejected, a high significance means the null-hypothesis is retained. The significance level for the tests is 0.01 and the confidence level is 99.0%.

Looking at the results from the independent-samples test, all null-hypotheses are rejected. It means that all three indicators (independent from each other) influence daylighting performance in both static and dynamic simulation. The boxplot of the used data is shown in Appendices 6 and 7. However, this result does not tell us if it is positively or negatively affected. To examine this, the normalised results are plotted to FSI/GSI/OSR rank (appendix 10). In Figure 50a to 50f, an example of the performance as a function of ranked urban density is shown. Mind that the x-axis is not scaled since only the rank matters in this analysis.

In the example of Figure 50a-f: FSI shows a stepwise relation but is more certain in static simulation. GSI indeed has an effect on performance but there is no clear trend line. OSR also shows a relation stepwise but is more convincing in dynamic simulation. Both FSI and OSR show a negative trendline, with a higher urban density generally resulting in lower performance.

A similar analysis is done for building floors ≥ 11, albeit for only three cities (Appendix 7). The conclusion is that lower FSI and OSR values correlate with higher performance in dense urban areas and that GSI does not show a trend: much similar to the analysis for building floors ≤ 10.

Within the scope of this thesis, it is not possible to perform to build further on these results with regression analysis between daylighting performance and urban density indicators. The effective population of urban density values is too small (max. 6), therefore the standard deviation and residual values would be too large. As a result, it is not possible to make concrete recommendations for FSI/OSR thresholds to design adequate residences. A recommendation for future research is to assess more urban patches so that the sample size is increased.

In conclusion, all three urban density indicators show to affect daylighting performance in both static and dynamic simulation. The FSI shows the most convincing correlation in dynamic simulation and OSR shows the most certain correlation in static simulation. GSI is found to be of influence on performance but no obvious trendline is discovered, suggesting future research is necessary to confirm this.

building floors <= 10

independent-samples median test	DF_{avg} (norm.)	TAI (norm.)
FSI	reject (.000)	reject (.000)
GSI	reject (.000)	reject (.000)
OSR	reject (.000)	reject (.000)

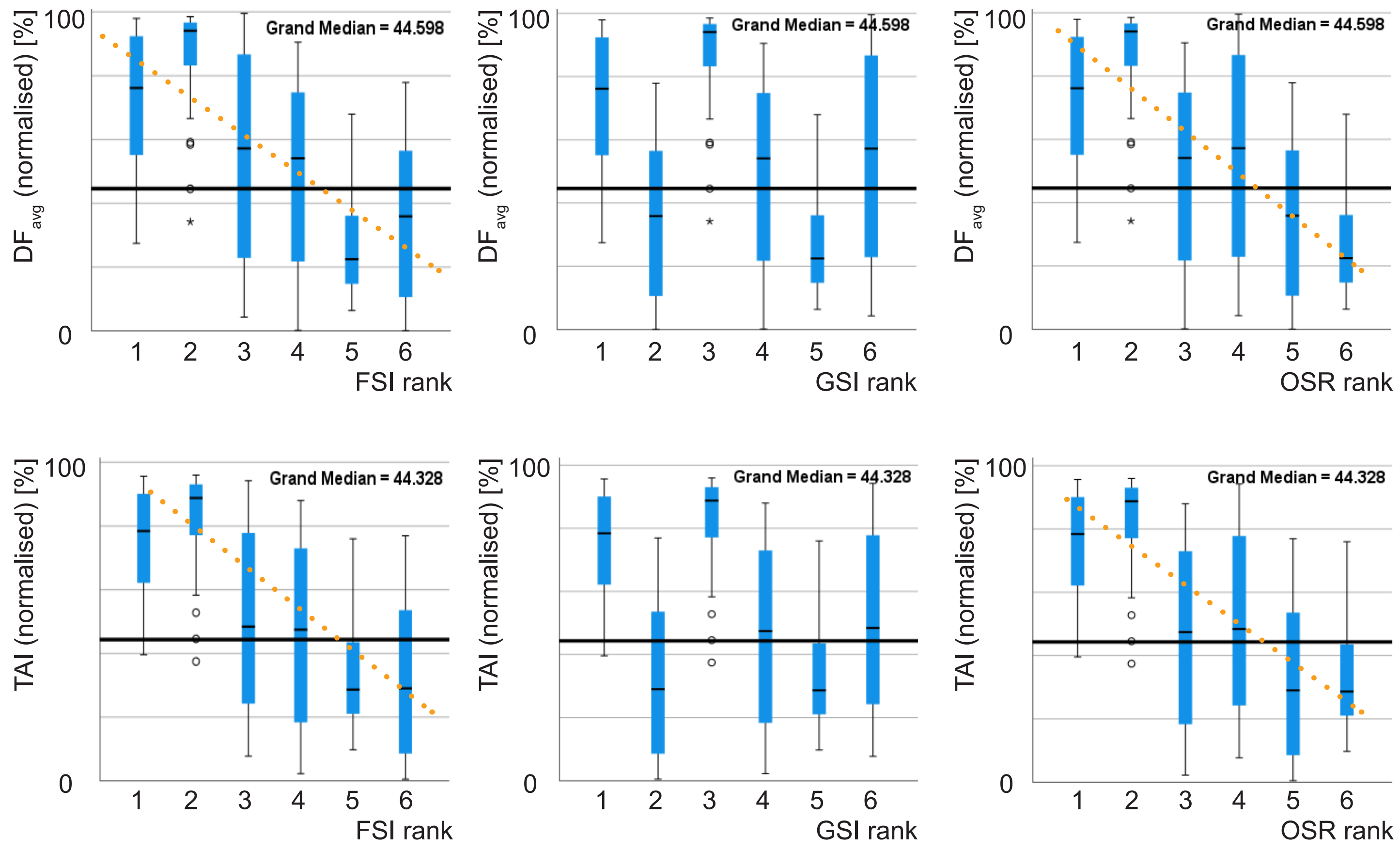
independent-samples Kruskal-Wallis test	DF_{avg} (norm.)	TAI (norm.)
FSI	reject (.000)	reject (.000)
GSI	reject (.000)	reject (.000)
OSR	reject (.000)	reject (.000)

building floors >= 11

independent-samples median test	DF_{avg} (norm.)	TAI (norm.)
FSI	reject (.000)	reject (.000)
GSI	reject (.000)	reject (.000)
OSR	reject (.000)	reject (.000)

independent-samples Kruskal-Wallis test	DF_{avg} (norm.)	TAI (norm.)
FSI	reject (.000)	reject (.000)
GSI	reject (.000)	reject (.000)
OSR	reject (.000)	reject (.000)

table 13: An overview of the null-hypotheses that are assessed in statistical analysis. Significance level is 0.01. Confidence level is 99.0%. In the blue square are the restults that are used for the analysis of Figure 28 a to f.



Stepwise, results are better in dynamic simulation

No trendline to be found in either simulation

stepwise, results are better in static simulation

Figure 50.a-f: Static and dynamic (normalised) performance as a function of different urban density indicators: from the statistical analysis for building floors ≤ 10. The dotted orange line is an estimated trendline.

building floor
The building floor level is a recurring aspect in many of the Figures, analysis and in conclusions. Early in the simulation process, it was clear that building floor level correlated strongly with daylighting performance. Where previously the sky view factor (SVF) was discussed throughout the results, the building floor level is discussed as a separate parameter in the results section.

An advantage of building floor level over other building parameters is its simplicity. There is no calculation required and immediately a mental image comes to mind. To build upon this simplicity, this study is interested in recommendations based on generic urban density data in combination with building floor level. In the *urban density characteristics* section, previous analysis on building floor level was done based on readings from Figures 45 to 49. Whilst the underlaying simulation data is the same, this analysis is done on a more statistical basis and inferential statistics is used to provide arguments for the recommendations made.

In this thesis, performance values are simulated with the use of two standard residential buildings. The walk-up apartment is simulated for medium-density urban areas. A taller residential tower is simulated in high-density urban areas. Because the urban characteristics of the two standard buildings are vastly different, they are regarded separately in the building floor analysis. For example, previously it was concluded that in the walk-up apartments, performance increased to 80% of its maximum as soon as building floor 4 (Figure 46 & 47). For the residential towers, this percentage is not reached at all in some cases (Figure 48 & 49). To overcome these differences, both buildings are analysed separately.

To give argument to the recommendations at the end of this section, the $DF_{2.1}$ and DA_{300} performance is shown as a function of the building floor in Figures 51a to 51d. The mean performance is plotted on the Y-axis and the error bars represent +/- 2 standard deviations (SD). In statistics, this means that at least 75% of the points fall within this range according to Chebychev's theorem (1867) if the distribution is unknown. Adversely, there is a chance of 25% that a point does not fall within the this range which is acceptable for this thesis. Note that this is different from a normal distribution, where +/- 2 SD means 95% of the points fall within the range.

Building floor: walk-up apartments
First, the walk-up apartment results are analysed. In Figures 51a and 51b we see that the error range is large, meaning that the performance spread is wide, the sample size is small or both. The sample size is n=20 per floor, so especially the performance spread is wide. This can be observed if we look back at Figures 46 and 47 where the performance spread is recognized earlier.

Another observation for the walk-up apartments is the mean performance increase with every building floor, as well as the minimum and maximum values. This strengthens the argument that there is indeed a relation. By reading the values from Figure 51a, we can conclude that a performance decrease of ca. 7.5% is expected in static simulation with a certainty of 75%. In dynamic simulations, no performance loss is expected based on the building floor according to the statistical analysis (Figure 51b).

Building floor: residential towers
If we do the same analysis for the residential towers, the results are more convincing. The sample size per building floor is n=24, increasing the certainty of the results and reducing the error. Here, the mean performance also increases for every building floor which can be seen in Figure 51c and 51d. The minimum, maximum and mean ranking is positively correlated with building floor level, suggesting a strong relation between performance and building floor.

Despite the error bars reaching 100% at building floor 11 in dynamic simulation, concrete recommendations can be made for lower floors. For building floors ≤3, the residences do not fulfil requirement anymore. With DA_{300} performance lower than 50%, it is certain for 75% these residences will not fulfil thesis requirement. For building floors 4 to 10, a maximum performance of 55-100% is expected with a certainty of 75% but with a possible performance as low as 0%.

From building floor 10 and upwards, the mean performance is sufficient in dynamic simulation but due to the large spread, the risk for insufficient performance remains. Because the simulation results do not exceed 100% of DA_{300} performance, the error decreases between building floors 10 and 23 but not to the point where we can ensure sufficient daylighting performance. It remains important to consider other aspects such as the SVF and building type, and orientation in dynamic simulation.

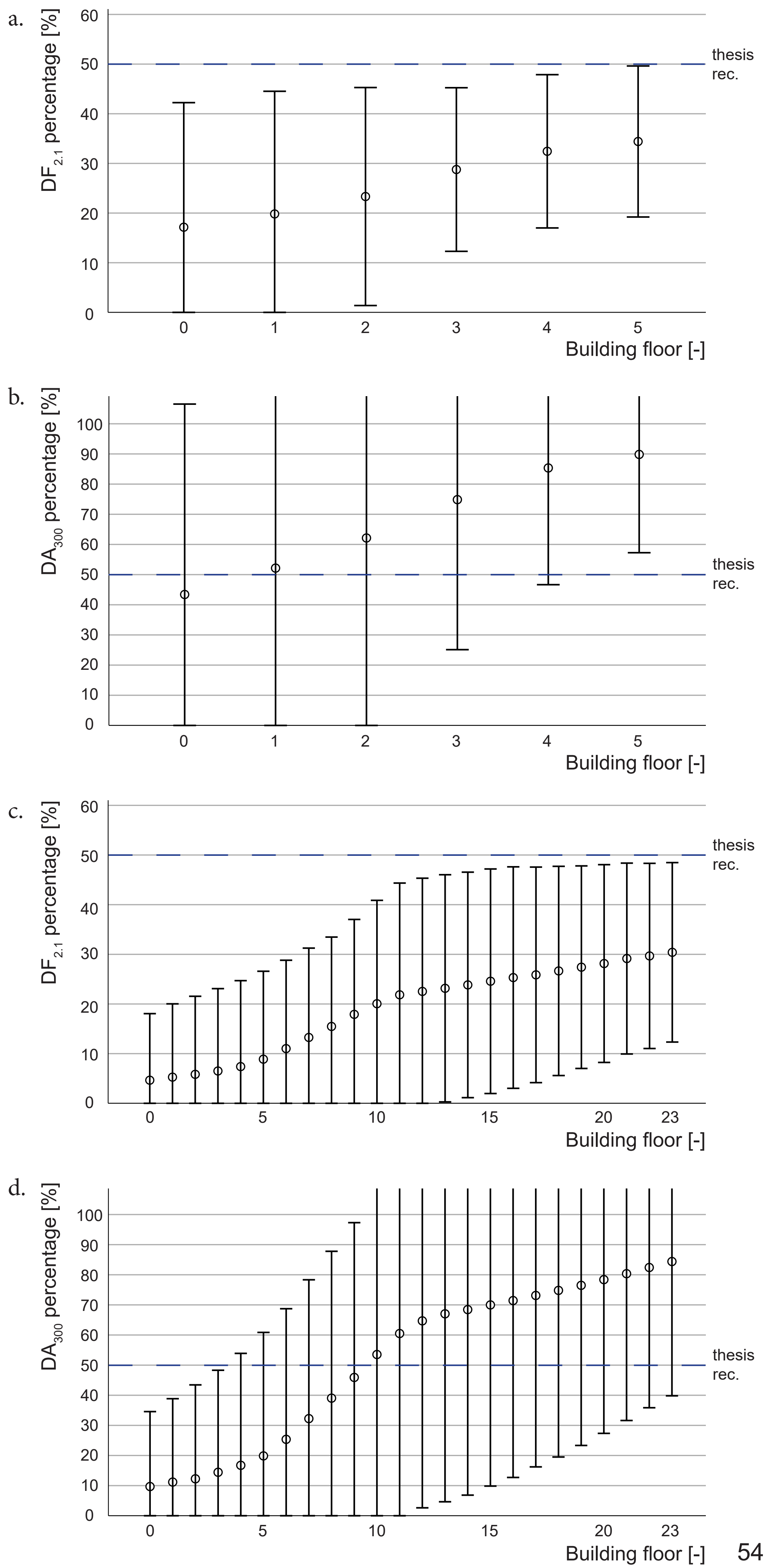


Figure 51.a-d: The mean performance percentages as a function of building floor for walk-up apartments (a & b) and for the residential towers (c & d). Error bars are +/- 2 SD.

In conclusion, for the walk-up apartments in the medium-density urban areas, there is a large spread of performance but only a performance loss of 7.5% can be expected in static simulation. In dynamic simulation, no performance loss is expected per se, and performance is likely to be sufficient from building floor 5 and upwards. Hence the advice is to design all residences in these areas with care but no avoidance is necessary.

For the residential tower buildings in the higher density areas, it is with 75% certainty that below building floor 3 the residences will not fulfil the thesis recommendation. Therefore the recommendation is that residences are avoided at these building floors. Between building floors 4 and 10, there is a risk that residences see a decrease in daylighting performance, with mean performance as low as 17% in dynamic simulation. Architects and designer should be very precautious with designing residences on these floors. For residences on building floors 10 and upwards, the mean performance is sufficient but although the standard deviation decreases up until building floor 23, the risk on insufficient daylighting remains.

All static simulation results are insufficient according to the thesis recommendation but a similar trend of performance increase is visible. The DF metric seems to react less dramatic to an increase of building level, possibly because orientation is not a factor in static simulation. No recommendations can be made based on the $DF_{2.1}$ percentage, but it seems that there is a loss of performance below building floor 11.

Building floor: normalised performance

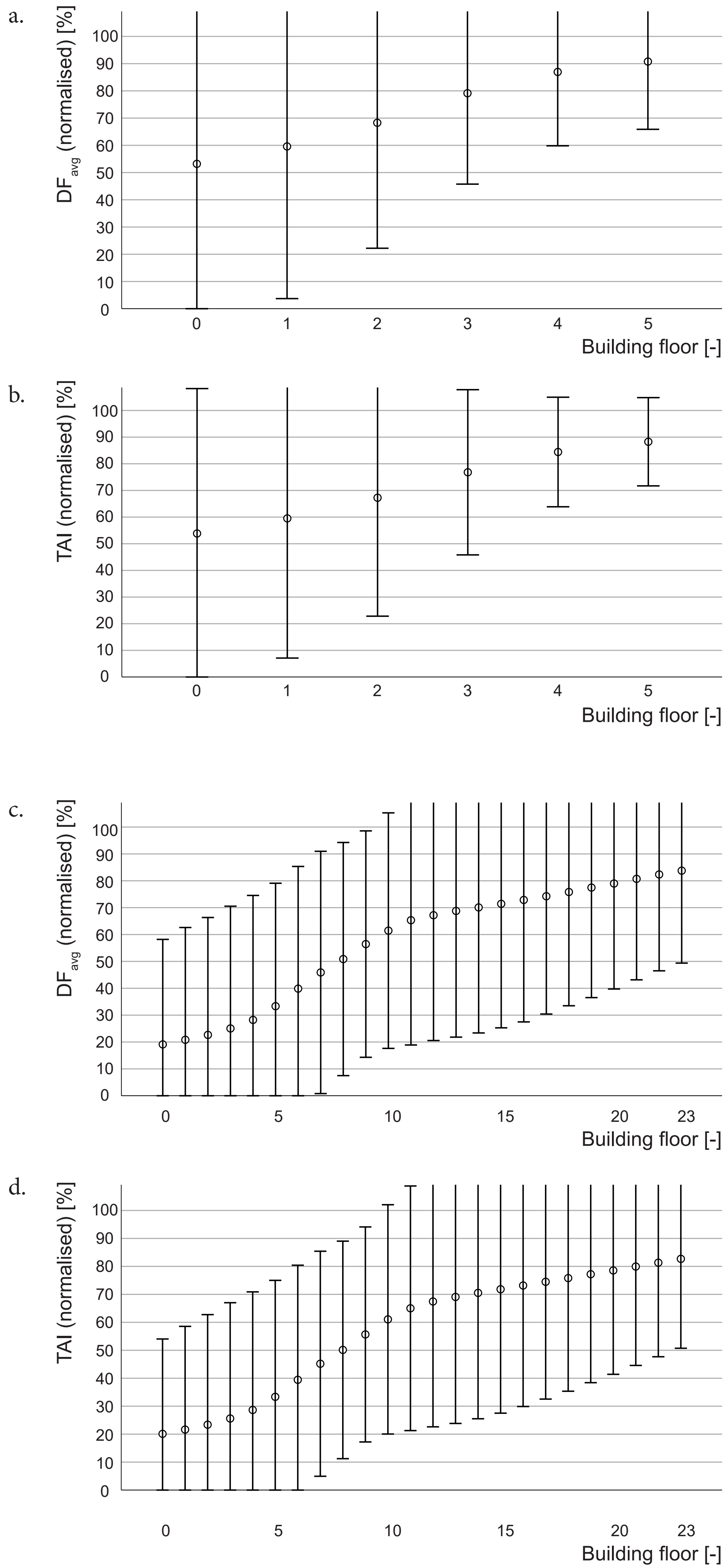
The $DF_{2.1}$ and DA_{300} metrics are assessing the thesis recommendation for performance in accordance with the EN 17037 methodology but do not provide us with a general performance decrease per building level, per building typology. This is because the metrics are not continuous: the maximum value is 100% and multiple residences can achieve it. Hence a similar analysis is performed for the continuous variant of the metrics: the DF_{avg} and TAI per sensor point. To factor out orientation differences and residential types, the results are normalised to the maximum performance of a residence with no urban context.

Looking at the normalised performance for the walk-up apartments in Figures 52a and 52b, the error spread is still large. Both Figures agree on a range of 100% for ground floor. Going upwards, the mean performance is increasing and the range is decreasing, meaning there is a correlation between performance and building floor. It seems that from building floor 4 and upwards, performance is at least 50% of the maximum with 75% certainty. Depending on how well a residence is designed, this means that the performance can be predicted if the maximum performance is known.

The same analysis for the residential towers also yields interesting results as an argument for recommendations. It seems that building floor is strongly correlated with performance with the maximum, the minimum and the mean performance being flawlessly ranked. This is for both static and dynamic simulation as can be seen in Figures 52c and 52d. Ground floor performance sees a 45% drop in performance with 75% certainty for both static and dynamic simulation. In a linear fashion, the expected maximum performance increases to 100% at building level 11. This is almost in accordance with the $DF_{2.1}$ and DA_{300} performance, where we recognized a cap at building floor 10 earlier.

In conclusion, the walk-up apartments in medium-density urban areas, the expected minimum performance increases with every building floor but the deviation range is too large to give numerical recommendations. It is relatively certain that at least 65% performance is achieved from the 5th building floor onwards, giving an indication of how much headroom must be considered if the thesis recommendation was to be reached within urban context. For residential towers in higher density urban areas, daylighting performance is expected to be only 55% at maximum on ground floor, increasing to 100% at building floor 10. All residences below building floor 10 should be designed with care since they will see a significant drop in daylighting performance compared to the simulation without urban context. From floor 8 and upwards, the mean performance is likely to be 50% of the theoretical maximum but it is for all buildings floors likely that there will be a significant decrease in performance.

Figure 52.a-d: The mean performance percentages (individual performance is normalised to the maximum performance of a residence without context) as a function of building floor for walk-up apartments (a & b) and for the residential towers (c & d). Error bars are +/- 2 SD.



Building floor: sky view factor
Previously, the only metric that led to similar conclusions on threshold values to ensure daylighting performance was the sky view factor (SVF). But this analysis has been done for each residential separately, leading to various minimum SVF recommendations. Counter to that, building floor seems an indicator across all residential types to estimate the risk on daylighting performance, hence it is thought that a relation between SVF and building floor can be analysed for better understanding of both.

If all SVF results are plotted as a function of building floor, the standard deviation is large as can be seen in appendix 9 (up to 60%). This is due to the differences between residential type A (double oriented facade) and B/C (single oriented facade). Also, the SVF is much higher in medium-density urban areas. This causes discrepancies, making the Figure in appendix 9 unusable without filtering the results. Therefore, the analysis is done separately for both urban densities and for single- (B/C) and double (A) oriented facades.

The SVF results from sections 'static DF simulation' and 'dynamic DA simulation' led to threshold values to fulfil the DA_{300} recommendation (p=75%). The threshold values for sufficient daylighting are plotted in blue in Figures 53a and 53c. The threshold values for insufficient daylighting (p=75%) are plotted for all Figures in red (Figures 53a to 53d). Since the static $DF_{2.1}$ recommendation is not fulfiled in any simulation, there is no 'safe' SVF threshold value plotted in any figure. Hence the conclusions only apply to the dynamic simulation results.

First, in Figures 53a and 53b the results for the walk-up apartments are shown. For type A, the safe SVF threshold value is SVF=61 (p=75%). For type B/C, there is no safe SVF threshold value for sufficient daylighting. According to the data, there is no building floor that has an acceptable probability to ensure the SVF threshold value. This is contrary to Figure 51b which concluded building floor 5 is likely to ensure sufficient daylighting. This may be because the SVF is a point-level indicator of performance and Figure 51b is using the performance data directly (resulting in more directness in its prediction of performance). Looking at the SVF threshold value for insufficient daylighting, type A residences have an acceptable risk from building floor 3 and upwards whereas type B/C residences have an acceptable risk from building floor 4 and upwards.

In conclusion, for walk-up apartments in medium-density urban areas it is recommended to be cautious when designing residences for the first three or four building floors, depending on the residential type. There is a significant risk that the SVF is insufficient to ensure sufficient daylighting at these levels. For the fourth building floor and up, there is a good probability that SVF values are sufficient (p=75%).

A similar analysis is done for the residential tower residences, as can be seen in Figure 53c and 53d. First, no building floor ensures the SVF threshold value for type A (p=75%) or for type B/C (no threshold value: always at risk). This does not mean that sufficient daylighting is not possible for the residential towers but rather that the SVF is not useful as an indicator for sufficient performance (based on p=75%). This is somewhat in line with the readings from Figure 51c where it was concluded that all building floors have a risk on insufficient daylighting (p≥25%) when comparing performance directly as a function of building floor. Furthermore, the probability for sufficient daylighting is too low under building floor 5, where the chances on sufficient daylighting are too small (p<75). Looking at the SVF threshold values for insufficient daylighting, type A residences have an acceptable risk on an insufficient SVF from building floor 10 and upwards (p=75%). The building floors in between floors 5 and 10 cannot be concluded on based on this analysis and therefore should be designed with care. For type B/C residences, the risk on insufficient SVF leading to insufficient daylighting is acceptable from building floor 21 and upwards: all other floors are at risk of insufficient SVF (leading to insufficient daylighting). These conclusions tell us that double oriented facades are more likely to avoid insufficient SVF values that can result in insufficient daylighting.

In conclusion for the residential towers in higher urban density areas, an advice is to avoid type A residences below building floor 5. The risk of insufficient SVF values is too large (≥75%). For type B/C residences, the performance is at risk for all SVF values. Between buildings floor 4 and 9, performance might be sufficient for type A residences but they need to be designed cautiously. Above building floor 10, the risk of inadequate performance in type A residences is less than 25% which is considered acceptable. For type B/C residences, building floors 21 and upwards have an acceptable risk on insufficient SVF values.

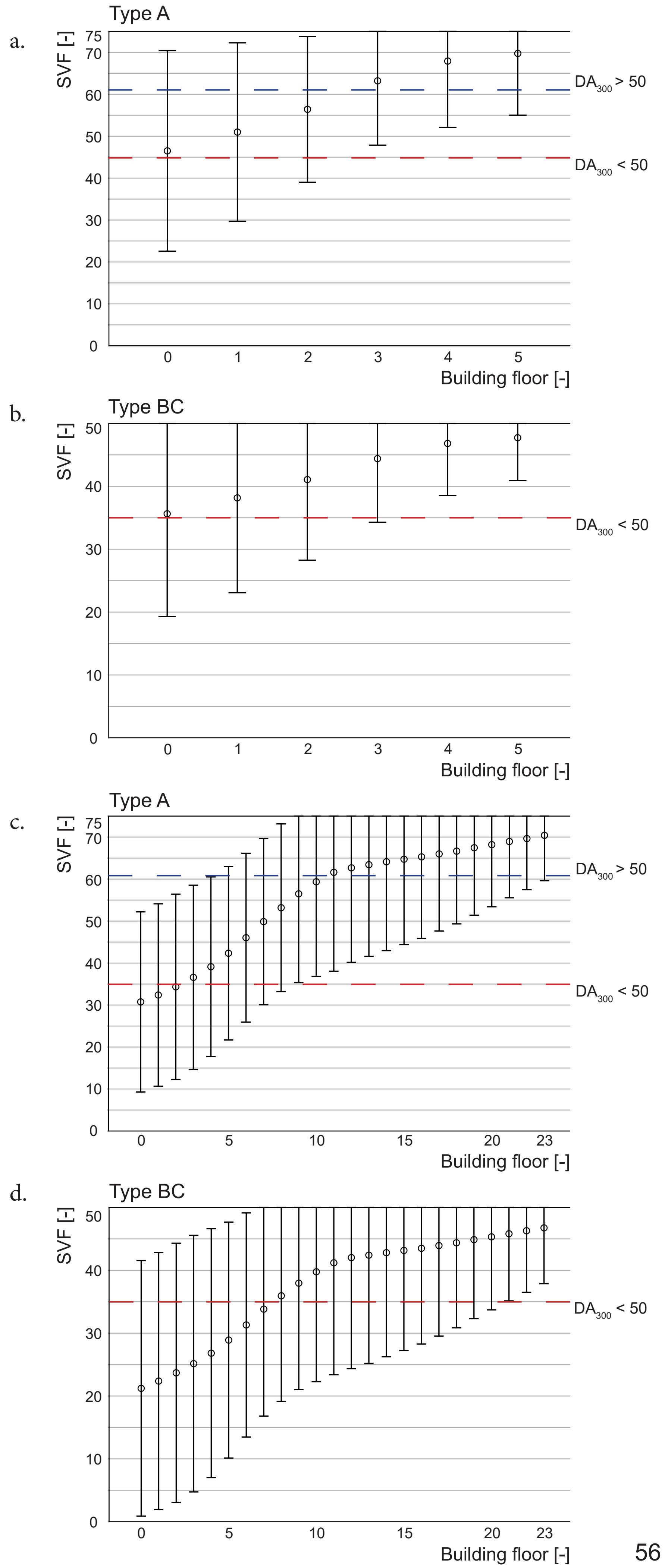


Figure 53.a-d: The mean SVF values as a function of building floor for type A residences (a & c) and type BC (b & d), separate for the walk-up apartments and residential tower buildings. Error bars are +/- 2 SD.

discussion

Recommendations

In this thesis, daylighting performance is assessed with static and dynamic simulation, as well as melanopic simulation. Two standard residential buildings are assessed, both in three different urban environments with different urban density characteristics, for a total of six different urban locations that are assessed. The buildings were built from three residence types A, B and C. For each residence, the performance was recorded as well as other aspects such as building floor, SVF, orientation and urban density.

The goal of this thesis is to integrate urban context in current daylighting assessment methodologies and to assess the effect on visual and non-visual light exposure. The results show that at least 50% of the residences see a performance reduction at least 36% in daylighting simulation (Figure 36). In specific cases, performance drops even lower. Based on the simulation results, the following recommendations can be made to better understand current assessment methodologies and to mitigate the risk on insufficient daylighting.

Using EN 17037 as a daylighting assessment methodology

- The EN 17037 assessment methodology is more useful in low & medium-density areas with little obstructions. The expected discrepancy in these urban areas is expected to be at least 25% (Figures 46 & 47). For higher density areas, the performance discrepancy is more than 60% in some cases (Figure 48). To avoid insufficient daylighting conditions, it is highly recommended to include urban context in daylighting assessment if bad daylighting conditions are expected.

- The results from static daylighting simulation are more pessimistic than for dynamic daylighting simulation. For all simulated residences, it is found easier to fulfil any performance requirement in dynamic simulation. This could lead to a strong incentive to only use the second method of the EN 17037 (CBDM method) if this is allowed by building code.

- Dynamic simulation results are sensitive to changing external reflectance values. For static simulation, the performance change is negligible. It is recommended that a standard set of external reflectance values is used in daylighting simulations. The values are found to be relatively consistent across multiple urban areas, therefore no large discrepancies are expected.

- To get realistic and comparable simulation results it is crucial for architects and daylighting designers to keep interior reflectance values reasonable and consistent. Both static and dynamic simulation are heavily affected by changes in interior reflectance (Figure 27). A standard set of interior reflectance values is recommended for assessment (and not a range of values as specified in the EN 17037). The set can either contain low values for a stricter assessment, or high values for a more forgiving assessment. An additional recommendation to this is to allow material properties for surfaces that are unlikely to change in material (e.g. ceilings, own exterior materials or cast-in-place flooring). This might stimulate designers and constructors to use better-reflecting materials, increasing indoor daylighting conditions.

- According to the dynamic TAI simulations, a total performance decrease of 13-56% is accepted to still fulfil the designed daylighting conditions, depending on orientation and external obstruction. This is a lower percentage than the expected performance loss of 25-60%, concluding that it is likely the designed level of daylighting will not be reached in multiple cases.

Expected impact on performance - building scale

- Building floor level, in combination with SVF, is a useful indicator for daylighting performance in urban areas, especially in early design stages (*Building floor: sky view factor*, page 56). For higher density urban areas under building floor 5, it is with 75% certainty that no residence will fulfil the recommended daylighting requirements. Residences should be avoided for these building floors. Between building floors 5 and 9, there is a great risk that residences are not adequately performing. Only type B/C residences have a probability on sufficient daylighting from the 21st floor and up. The general advice is to design all residences in high urban density areas with special care for daylighting.

- For medium-density urban areas, the building floor is a useable indicator to avoid insufficient daylighting. For no building floors adequate daylighting conditions is certain but it is unlikely to have insufficient daylighting conditions above building floor 2 for type A residences and above building floor 3 for type B/C residences (Figures 53a & 53b)

- The SVF is useful in statistical analysis to derive threshold values for sufficient performance in both static and dynamic simulation. The probability that the threshold value holds true is at minimum 75% for error bars +/- 2 SD. This methodology of risk estimation can also be applied for different requirements. Contrary to this, the SVF also can indicate insufficient performance with a risk of more than 75%. This makes the SVF a good point-level indicator of performance which can be calculated at an early design stage.

- If a residence fulfils the thesis recommended daylighting requirements, there is little to no risk on insufficient non-visual stimulus throughout the year under clear sky conditions. For this analysis, the MA and MI metrics seem suitable in articulating the performance differences (Figures 39 & 41. Artificial lighting is still needed in wintertime but this is an advice for all buildings in the Netherlands.

- If a residence fulfils the BBL daylighting requirements, there is a serious risk on inadequate non-visual stimulus throughout the year, even under clear sky conditions. For this analysis, the MA and MI metrics seem suitable in articulating the performance differences (Figures 39 & 41). Additional artificial lighting is definitely necessary to ensure sufficient non-visual stimulus, especially for residences that are obstructed by external buildings.

Expected impact on performance - urban context

- The FSI and OSR density indicators show a correlation with daylighting performance in both static and dynamic simulation. However, no concrete recommendations can be given due to the small population size of the analysis. The FSI holds a stronger relation in dynamic simulation and the OSR shows a stronger relation in static simulation. In both cases, a higher urban density results in lower mean daylighting performance. GSI seems to be correlated to performance but no (linear) trend was found.

- Ground reflectance values have a large influence on the performance of residences on ground floor but have little to no effect for residences higher up. This makes the ground reflectance value especially important for simulation in medium-density cities with little obstruction. In practice, the ground reflectance values do not vary much, making it not a recommended mitigation strategy to improve performance with. It is further recommended that a single ground reflectance value is used in daylighting assessments for consistency and comparability.

- External building reflectance has a significant impact on daylighting performance but only in dynamic simulation. A realistic maximum building reflectance is ca. 45% and this may increase indoor performance by 100% compared to a situation with a standard building reflectance of ca. 15%, depending on orientation and obstruction. It is recommended to use a standard external building reflectance value in daylighting assessment methodologies but allowing realistic values in case the building is likely to not change in the future (i.e. monuments or infrastructure).

Mitigation strategies

- If there is no performance headroom in the design of a residence, it is probable that it will not fulfil daylighting requirements with urban context integrated in the assessment methodology of choice. Therefore it is strongly recommended that the residence is either designed with urban context in mind or that a mitigation strategy is at hand in case performance is found insufficient in a further design stage.

- In higher density urban areas, an effective method to increase daylighting in residences is to avoid insufficient daylighting in the first place. Not placing residences on the lower building floors but rather other functions e.g. parking, cinemas or hospitality, is best practice to avoid possible issues with daylighting.

- The interior layout of a residence can sway the results up to 15% in daylighting simulation. An interior layout with no interior walls performs up to 15% better than the same residence with interior walls in dynamic simulation (Figure 27). Conversely, depending on the interior layout of a building type the performance may decrease with the same percentage.

- Daylighting performance and glass transmission values are linearly correlated (Figure 29). An increase in glass transmission results in an equal increase in daylighting performance. This is found to be the most effective and a very low-impact design strategy to increase daylighting performance but should be applied with care as it also influences the SHGC, thermal comfort and acoustical performance.

Limitations

This thesis is assessing the effect on daylighting performance if urban context is integrated in current assessment methodologies. However, there are limitations that should be considered when reading and interpreting the results.

In order to give recommendations on improving daylighting performance in the built environment, data sets are needed that are large enough for statistical analysis to strengthen the argument for different recommendations and conclusions. Six different urban location were assessed in this thesis but their individual urban density is only a singular value per indicator. Effectively, this resulted in a population size of only 6 independent samples if the relation between performance and urban density is analysed. This has resulted in not enough data on different urban areas to perform regression analysis. Also, arguably the 6 independent samples were not completely homogeneous with two residential buildings assessed, and not 1 identical building. This impacts the comparability of the results and made analysis and comparison harder to follow.

Another limitation of the study is the method on how performance was assessed throughout the report. In most Figures, performance is expressed as the floor area percentage that fulfil DA_{300} or $DF_{2.1}$ requirement. However, this limits the assessment for different requirements such as DA_{144} (BBL) or DA_{500} (EU medium). Currently, if another study does not agree on the thesis recommended values, an extra simulation run would be necessary to gather this data, requiring a significant time investment.

For the melanopic assessment, a small number of residences are analysed of 1 residential type B. While the results seem valid and the MA/MI metrics are suitable in expressing differences in performance, it remains a point-in-time observation under 'best case scenario' conditions. The melanopic performance is assessed on a sunny day with favourable SPD properties of the sky. This is not representative for typical weather conditions in the Netherlands or for similar climates. In the current version of LARK, it is not possible to have variable sky conditions in a simulation. Additional research is necessary to assess the melanopic performance under sub-optimal sky conditions.

Further research

As a follow up to the recommendations and limitations of the report, proposals for future studies are made.

First, in order to assess daylighting performance as a function of urban density indicators, it is recommended that only 1 residential building is simulated and that the statistical population is increased. Creating more comparable results and more data entries will increase the statistical significance and reduce the standard deviation. This thesis demonstrates how this data can be analysed statistically but currently there are not enough data entries for correlation or regression analysis.

Secondly, the recorded data is only applicable to the requirement of DA_{300} and $DF_{2.1}$. For future studies, it is highly recommended to record the 50th and 95th percentile performance as well to increase the versatility of the results. For this study, the DA_{300} and $DF_{2.1}$ were a good fit for the results but it cannot be reused for different threshold performances without rerunning all simulations.

Thirdly, the initial focus of the report was on fulfiling photopic daylighting requirements and then assessing melanopic performance afterwards. For future studies, it would be of interest to see if the performance decrease in urban context is different for melanopic light exposure. Now, design recommendations have been made based on photopic metrics only, and it would be interesting to see if melanopic metrics would give similar results.

The fourth suggestion for future research would be on melanopic autonomy and melanopic isotropy metrics as defined by this thesis. Early results show that the metrics are suitable for the expression of performance differences but it is unknown what the real world performance would be under non-ideal sky conditions. Furthermore, additional research is necessary to develop a benchmark methodology for melanopic performance. This benchmark can possibly be similar to the DF assessment under overcast sky for testing a worst case scenario, or it could assess different days throughout the year for year-round performance.

conclusion

The thesis research was about daylighting in urban areas and the effects of integrating urban context on visual and non-visual light exposure. The main research question was as follows:

What are the design consequences in Dutch urban areas when context is integrated in current daylighting evaluation methods, regarding visual and non-visual levels of daylight?

To answer this question, static and dynamic daylighting simulation has been performed for standard residences in various urban areas.

The simulations in this report are run in compliance with the EN 17037 assessment methodology, with realistic exterior and interior reflectance values. Two simplified buildings are modelled and their results are simulated in six different urban locations. Publicly available databases are used for 3D geometry and reflectance values in the built environment.

In the worst scenarios, daylighting is decreased by >90% due to its urban environment. It was found that the sky view factor (SVF) and the building floor are good indicators for performance in early design stages. This leads to the recommendation to avoid positioning residences below building floor 5 in high-density urban areas. Single oriented residences have a significant risk of insufficient daylighting conditions below building floor 21, whilst double oriented residences have a risk on insufficient daylighting conditions below building floor 11. For medium-density urban areas, all residences should be designed with care for daylighting conditions but the performance decrease can be mitigated.

Urban density indicators are found to be correlated to daylighting performance, though no design recommendations can be made solely based on the data of this thesis. FSI and OSR suggest a convincing correlation where higher urban densities result in lower daylighting performance but future research is necessary for regression analysis and concrete recommendations.

In case the daylighting performance is found insufficient, mitigation strategies such as increasing glass transmission values, interior reflectance values or external building reflectance were found to be effective in increasing performance in both static and dynamic simulations. Another effective mitigation strategy is to avoid bad daylighting conditions in the first place by not placing residences on the lower building floors but rather other functions that require less daylighting, especially in high-density urban areas.

Two novel metrics are introduced to assess melanopic performance in residences: melanopic autonomy and melanopic isotropy. They have shown to be useful and reliable in assessing the performance and behaviour of non-visual light stimulus throughout the assessed time period.

Using the metrics of Melanopic Autonomy (MA) and Melanopic Isotropy (MI), the non-visual light stimulus is considered sufficient and healthy for residences that are compliant to the EN 17037 minimum requirement of $DA_{300} \geq 50\%$. Artificial lighting is still necessary in wintertime to amplify melanopic performance but this is an advice for all buildings in the Netherlands.

For residences that are compliant to the BBL requirement of $DA_{144} \geq 50\%$, there is a risk of insufficient melanopic light exposure, depending on orientation and time of the year. Either the photopic daylighting exposure needs to be improved or artificial lighting is needed to supplement the residents with sufficient non-visual stimulus throughout the year.

Future studies may assess more different urban locations to find a more convincing correlation between daylighting performance and urban density indicators such as the FSI, GSI and OSR. The melanopic assessment methodology, as used in this paper, has shown to be reliable and useable, and could lead to a different approach to designing healthier residences in the future.

This thesis report has simulated realistic residences in Dutch urban context to assess their performance in real world situations. This helps to better understand the impact of urban context on visual and non-visual light exposure. The results from this thesis can be used by daylighting designers and architects who are interested in ensuring sufficient and healthy daylighting conditions in the residences they design: not only in digital environments but in the real world.

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reflection

Subsequently on the topic of ‘one million homes before 2030’ my master graduation is about ensuring daylighting performance in Dutch urban areas and the effect of considering urban context in assessment methodologies.

A motivation for this graduation topic from the beginning is a scheduled change in building regulation regarding daylighting assessment. No longer is an equivalent daylighting surface area required in a design but the design needs to fulfil a minimum daylight factor. This is interesting because not only does it change the metric with which we measure ‘performance’ but it poses a challenge for Dutch architects and builders to gather knowledge about this metric and its assessment methodology (EN 17037, 2018).

Process

To assess performance in Dutch urban areas, I chose locations that had different characteristics and had to find a way to describe the differences. Soon enough, with the help of extensive literature review and feedback from my mentors, I had found a method to scientifically filter different urban areas and a method to assess performance

A total of six locations were assessed on their daylighting performance. A standard residential tower and a standard walk-up apartment were simulated in the different locations to create a database with all their performance metrics. This is done for both static and dynamic simulation methods.

Because the EN 17037 and the Building Code 2012/BBL offer two methods of assessing daylighting performance, the number of simulations became overwhelming rather quickly. Performing a simulation for 9 residences, for 23 levels, for 6 locations, with 2 methods and multiple metrics quickly became a great task. Data, file and script management became essential early in the process: something I did not expect and had no experience with.

Especially after P2 when I started running simulations, figuring out the exact methodology was a process of trial and error. Mistakes were made, bugs were found in software and small things were overlooked. However, I am glad I started early with running simulations to smooth things over: well before the stress kicked in or any mandatory deadlines. Even though this took away the focus from the thesis report, the progress has been consistent between P2 and P3.

After receiving constructive feedback during P2 and P3 assessment, the momentum was used to explore melanopic performance for some residences and to write down all the results in the thesis report. This was an extensive task: summarizing 685 data entries for various independent variables required a lot of care. Still, some results are confusing but breaking it down in smaller pieces and tackling the variable one by one helped a lot.

Mentoring and feedback

My attitude towards the feedback moments, tutoring sessions and meetings is mostly positive. I think both my mentors know what I am doing and why I am doing it my way, which is giving me confidence in the process and my progress. Because of this, I do not feel the urge to have a meeting every week or two weeks. Only time will tell if this was righteous but especially after P2 I was able to share my preliminary results and harvest valuable feedback. It always led to objectives for me to tackle, which I think is exactly what mentoring and tutoring should provide. In the last stage of graduation, more of the focus was on writing the thesis and processing the data, hence mentoring became less useful. However, this makes sense: at some point we just have to continue with our work and make big steps.

Did my approach work?

From the beginning I had a strong assumption that the urban context had a large penalty on daylighting performance. I expected a discrepancy between having no context and simulation with context but I could not have thought the results were this far off eachother.

What worked great is assessing multiple locations which resulted in a large pile of useful data. Simulating a tall building yielded many data entries which was great for statistical analysis. This exploits correlations and regressions I could not have discovered if I solely focussed on one project or one location.

However, not all went well. In my eyes, a neglected part of my original graduation plan is the analysis of residences on their melanopic daylighting performance. Because I wanted to analyse the worst performing (photopic) residences, I had to round up that part of the research first before I could even think about running melanopic simulations. It forced me in being very selective in the results that the melanopic assessment needed to generate and how to get those results in a tim-effective manner. Eventually, the results were useful for assessment but I would have liked to have seen it being more extensive in order to conclude with more detail on melanopic performance in the built environment.

Learning from my own work

My graduation project has been fun to do, and I am positively surprised how much motivation I had throughout the year. Originally, I was sceptical about doing a single project for an whole year but looking at the relevance of my project and to which extent I can go into the topic of daylight, it motivates me to keep digging deeper. Of course, this is also a pitfall but luckily my mentors warned me in time that my P1 plans were quite ambitious.

This project being my first proper experience with Rhino, grasshopper, honeybee AND radiance, I can conclude I have learned many valuable tools for in the future. The possibilities and limitations of all the software I have used are certainly coming in handy when this graduation period ends, and new opportunities start. The computational tools forces one to approach problems in an analytical manner: an attitude towards problem solving from which I learn a lot from.

In the final stretch, my challenge was incorporating melanopic performance in my thesis and doing it in a time-efficient way. A risk that came with this was that with postponing it, there was less time to solve unexpected problems and less time to analyse the data. Luckily, all went well and the analysis yielded reliable and useable results.

Even though I started writing my thesis well on time, it remained a challenge to finish everything on time. The amount of Figures (ca. 107) was intense and it consumed a lot of my time preparing and exporting them. It raises the question if some things could not have been more streamlined or left out..

In conclusion, I look back with a positive feeling about the results of my thesis. Even though the direction of the thesis was not what I initially intended, it was fun to work with various software packages and to learn about daylighting in general. The conclusion sparks a discussion and I believe it can teach us valuable lessons about daylighting in the urban context.

Societal impact

Modern architects face the challenge of designing more sustainable buildings as well as ones that perform better and are affordable. However, not always are different building requirements in accordance with each other. In case of the topic of this thesis, better daylighting conditions have lead to higher energy consumption and lower thermal comfort in the past. The average glass surface area of a residence tends to have been decreasing in the past years, resulting in debatable daylighting performance in practice.

The result of this trend is insufficient daylighting conditions in newly built residences, especially in the urban environment. Urban context is not considered in current assessment methodologies, resulting in significantly lower performance in the real world than calculated in the simulation models. This might lead to an unhealthy and energy inefficient building design with the residents carrying the trouble.

It is important that our daylighting design provides our bodies with sufficient visual and non-visual stimulus. This increases our health and therefore our wellbeing. This thesis will do research on the current state of daylighting conditions in a realistic residence in different urban environments, and it will propose improvement strategies if performance is found to be insufficient.

Scientific impact

Existing research on the impact of urban context on daylighting performance is often simulating with infinite urban canyons and focussing on photopic performance only. This thesis is trying to generate more information on simulation performance with real world geometry and reflectance values, straying away from hypothetical situations and more towards a realistic setting. Also, melanopic performance is assessed in relation to existing urban context, using two novel metric: melanopic autonomy (MA) and melanopic isotropy (MI). Lastly, daylighting performance as a function of urban density is analysed which has led to interesting results on a potential correlation.

Appendix 1: Location density values

Amsterdam Zuidas

data	orientation	noemer_ID	Shape_Area	FSI_22	GSI_22	OSR_22	L_22
net building block	-	1351	2560	13.06	0.72	0.02	5
gross building block	-	1351	5645	5.21	0.33	0.13	5.11
gross building block	o	1350	6866	3.19	0.49	0.16	4.36
gross building block	zo	1345	2468	4.50	0.19	0.18	4.36
gross building block	z	1338	3029	4.01	0.35	0.16	4.36
gross building block	zw	1335	2900	2.99	0.45	0.18	2.41
gross building block	w	1352	4891	5.44	0.34	0.12	5.00
gross building block	n	1370	12886	2.70	0.53	0.17	4.53
gross building block	no	63	40548	2.05	0.32	0.33	5.09
average incl. location				3.76	0.38	0.18	4.40
weighted average incl location				2.87	0.37	0.25	4.78
gross neighbourhood		125	203171	2.85	0.3	0.25	5.08

Eindhoven

data	orientation	noemer_ID	Shape_Area	FSI_22	GSI_22	OSR_22	L_22
net building block	-	1524	5310	9.44	1	0	9.41
gross building block	-	1524	16715	3	0.32	0.23	9.41
gross building block	o	1529	15835	1.52	0.36	0.42	4.19
gross building block	zo	1448	5435	0.85	0.53	0.55	1.48
gross building block	z	32	28368	3.16	0.35	0.21	8.83
gross building block	zw	1485	16428	0.85	0.20	0.94	4.18
gross building block	w	1539	12599	0.69	0.39	0.88	1.78
gross building block	w	1527	1975	1.18	0.26	0.63	4.42
gross building block	nw	1570	7222	1.22	0.31	0.57	3.50
gross building block	n	1612	34256	1.28	0.37	0.49	3.34
average incl. location				1.53	0.34	0.55	4.57
weighted average incl location				1.77	0.34	0.49	5.20
gross neighbourhood		3	172623	1.78	0.32	0.38	5.51

Delft

data	orientation	noemer_ID	Shape_Area	FSI_22	GSI_22	OSR_22	L_22
net building block	-	340	423	1.04	1	0	1.04
gross building block	-	340	3449	0.13	0.12	6.77	1.04
gross building block	n	355	7232	2.30	0.19	0.35	11.88
gross building block	o	345	9040	0.51	0.20	1.57	2.62
gross building block	z / w	341	14080	0.89	0.14	0.97	6.54
average incl. location				0.96	0.16	2.42	5.52
weighted average incl location				1.01	0.18	1.59	6.07
gross neighbourhood			108233	1.18	0.15	0.72	7.61

Utrecht

data	orientation	noemer_ID	Shape_Area	FSI_22	GSI_22	OSR_22	L_22
net building block	-	1529	1958	3.01	0.99	0	3
gross building block	-	1529	3107	1.9	0.62	0.2	3
gross building block	n	1541	3333	2.07	0.59	0.20	3.44
gross building block	o	1532	712	2.35	0.66	0.14	3.52
gross building block	z	1516	31287	1.69	0.58	0.25	2.70
gross building block	z	1478	10429	1.37	0.53	0.34	2.58
gross building block	w	1568	9021	2.13	0.65	0.16	3.27
average incl. location				1.92	0.61	0.22	3.09
weighted average incl location				1.74	0.59	0.25	2.84
gross neighbourhood		60	171010	1.65	0.53	0.28	2.84

Rotterdam North

data	orientation	noemer_ID	Shape_Area	FSI_22	GSI_22	OSR_22	L_22
net building block	-						
gross building block	-	4635	55242	1.17	0.28	0.62	3.94
gross building block	n	4713	17001	1.3	0.47	0.41	2.73
gross building block	no	4646	6461	1.32	0.51	0.37	2.59
gross building block	o	4623	6845	1.39	0.47	0.38	2.99
gross building block	zo	4566	20506	1.14	0.34	0.58	3.25
gross building block	z	4472	10093	1.36	0.38	0.46	3.59
gross building block	zw	4510	10396	1.33	0.34	0.5	3.87
gross building block	w	4613	20662	1.06	0.32	0.64	3.31
gross building block	nw	4680	16221	1.09	0.33	0.61	3.25
gross building block	nw	4622	2599	1.15	0.3	0.61	3.72
average incl. location				1.231	0.374	0.518	3.324
weighted average incl location				1.19	0.34	0.56	3.46
gross neighbourhood				1.16	0.33	0.58	3.45

Rotterdam Maritim

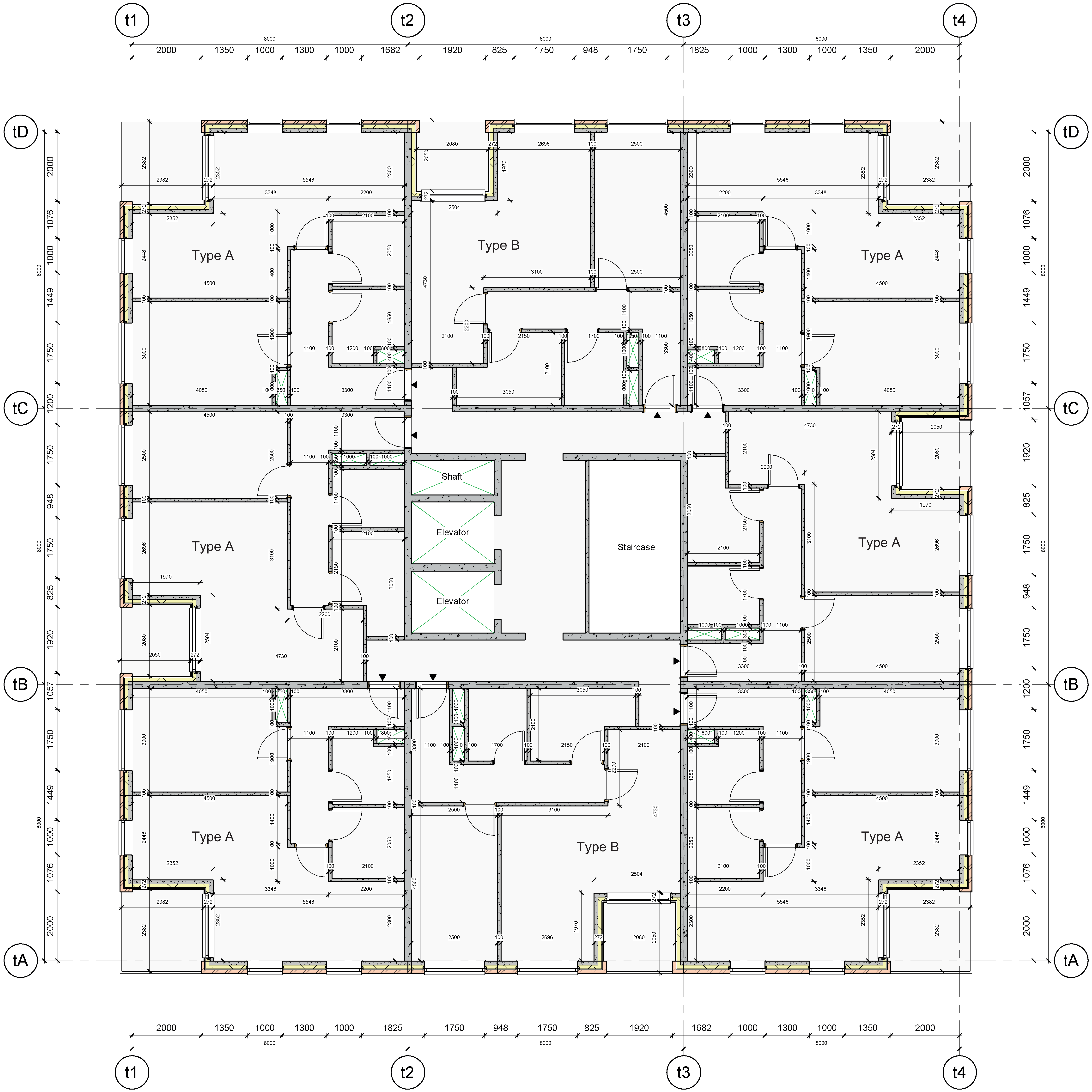
data	orientation	noemer_ID	Shape_Area	FSI_22	GSI_22	OSR_22	L_22
net building block	-	3709	5301	7.98	1	0	7.81
gross building block	-	3708	10735	3.94	0.49	0.13	7.81
gross building block	n	3751	12058	3.77	0.41	0.16	9.03
gross building block	no	3761	6891	2.35	0.37	0.27	6.31
gross building block	o	3716	6625	4.28	0.55	0.11	7.75
gross building block	zw	195	31889	2.28	0.07	0.41	10.89
gross building block	w	3698	12725	3.68	0.54	0.12	6.76
gross building block	nw	3724	7020	2.25	0.45	0.24	4.85
average incl. location				3.22	0.41	0.21	7.63
weighted average incl location				3.04	0.33	0.25	8.58
gross neighbourhood		1	1478065	1.7	0.26	0.44	5.47

Appendix 2: Building context reflectance values

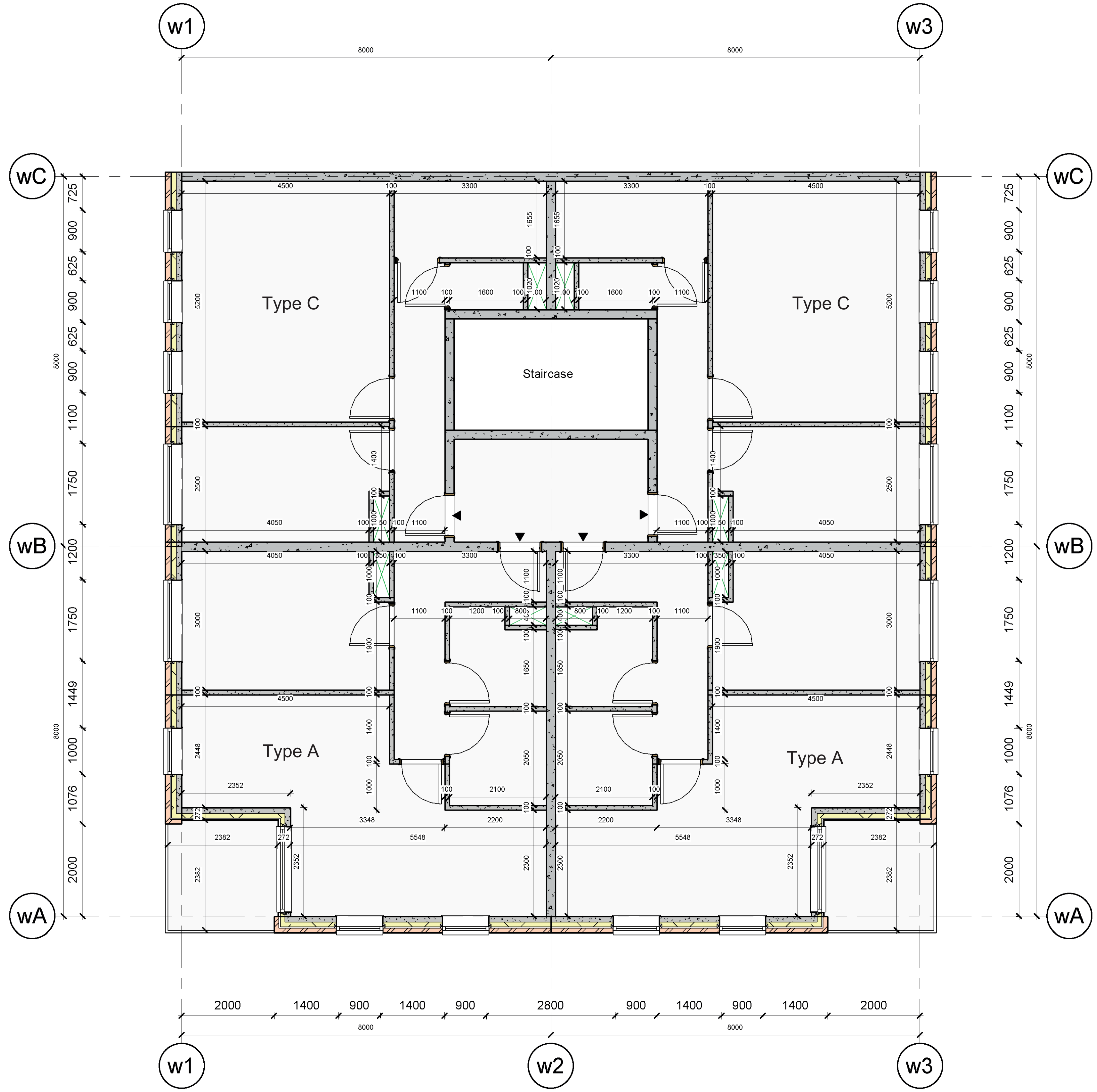
An illustration of the calculation method for reflectance values in the built environment. Typologies and time periods originate from RVO example residences (RVO, 2022). Material reflection data is from SpectralDB (2023) and LBNL (n.d.). Own source.

	residential type	year	façade type	glass system	WINDOW ID	blind façade [m2]	window [m2]	calculated total [m2]	glass percentage [%]	Reflectance blind façade	Reflectance glass	weighted average reflectance
Delft	rowhousing	'65-'74	masonry	double	2	37.67	24.98	62.65	40%	0.138	0.14	14.04
	gallery housing	'65-'74	masonry	single	1	23.94	20.07	44.01	46%	0.138	0.08	11.25
Rotterdam noord	walk-up housing	'75-'91	masonry	double	2	30.40	11.19	41.59	27%	0.138	0.14	13.96
	rowhousing	pre '45	masonry	single	1	41.58	19.30	60.88	32%	0.138	0.08	12.02
	walk-up housing	pre '45	masonry	single	1	29.86	11.46	41.32	28%	0.138	0.08	12.25
	maisonette	pre '45	masonry	single	1	40.58	17.92	58.50	31%	0.138	0.08	12.08
Rotterdam centrum	flat housing	pre '64	masonry	single	1	32.80	11.70	44.50	26%	0.138	0.08	12.33
	flat housing	'65-'74	masonry	single	1	33.80	15.07	48.87	31%	0.138	0.08	12.07
	flat housing	'75-'91	masonry	double	2	33.60	10.99	44.59	25%	0.138	0.14	13.95
	flat housing	'92-'05	masonry	double	2	36.22	16.81	53.03	32%	0.138	0.14	13.99
	flat housing	'06-'14	masonry	double	2	33.94	20.42	54.36	38%	0.138	0.14	14.03
	flat housing	'15-'18	masonry	double low-E	10	15.14	17.86	33.00	54%	0.138	0.12	12.83
Amsterdam Zuidas	flat housing	'15-'18	masonry	double low-E	10	15.14	17.86	33.00	54%	0.138	0.12	12.83
	gallery housing	'65-'74	masonry	single	1	23.94	20.07	44.01	46%	0.138	0.08	11.25
	office (generic)	'99	cladding	double low-E	10	1.00	1.00	2.00	50%	0.200	0.12	16.00
Eindhoven	walk-up housing	pre '45	masonry	single	1	29.86	11.46	41.32	28%	0.138	0.08	12.25
	walk-up housing	'15-'18	masonry	double low-E	10	34.46	11.56	46.02	25%	0.138	0.12	13.35
	parking garage	'01	masonry	N/A	N/A	1.00	1.00	2.00	50%	0.138	0.00	6.90
	office (generic)	'32 - '81	cladding	double	2	1.00	1.00	2.00	50%	0.200		10.00
	office (generic)	'09	cladding	double low-E	10	1.00	1.00	2.00	50%	0.200	0.12	16.00
Utrecht	rowhousing	pre '45	masonry	single	1	41.58	19.30	60.88	32%	0.138	0.08	12.02
	walk-up housing	'75-'91	masonry	double	2	30.40	11.19	41.59	27%	0.138	0.14	13.96
	walk-up housing	'15-'18	masonry	double low-E	10	34.46	11.56	46.02	25%	0.138	0.12	13.35

Appendix 3: Residential tower floor plan



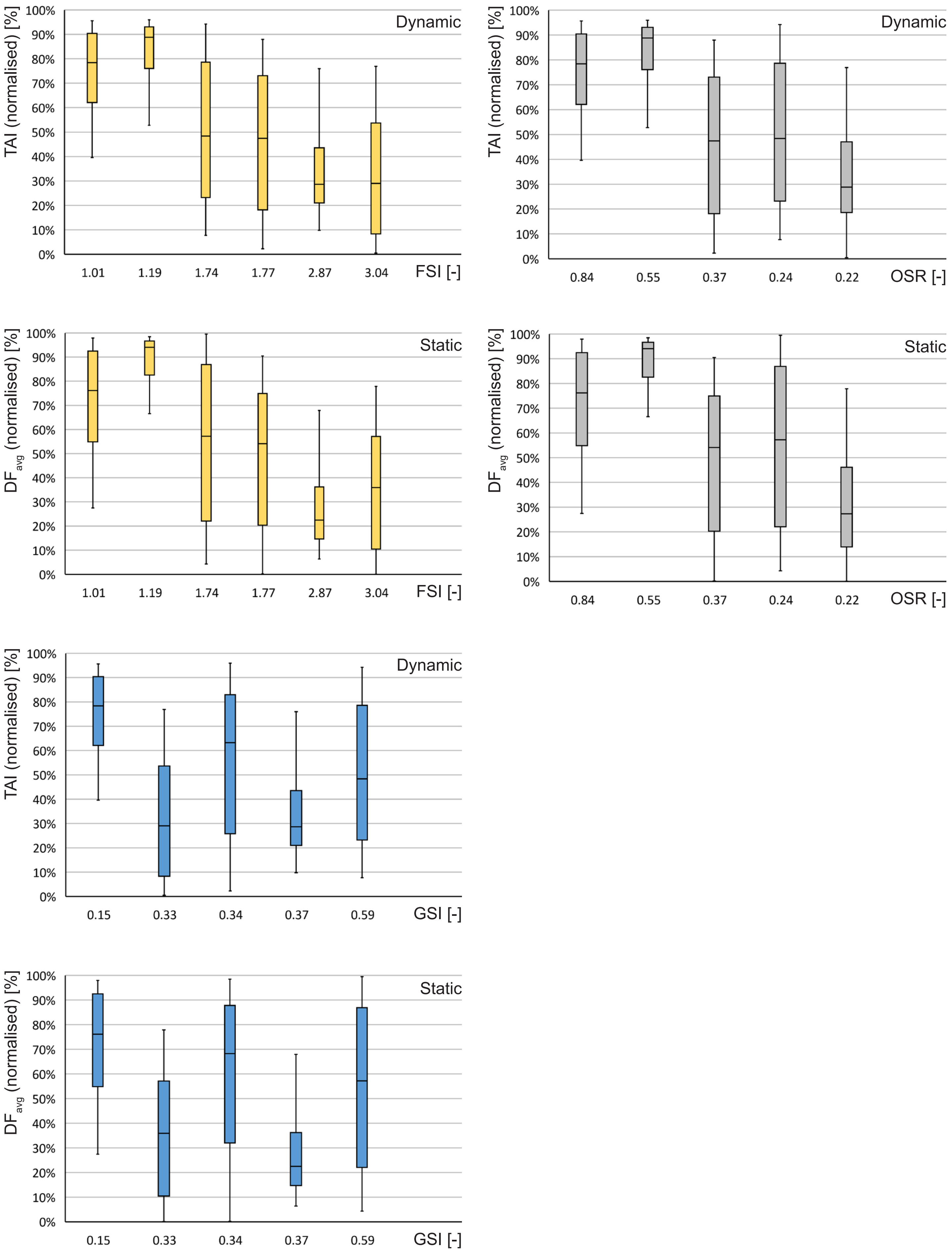
Appendix 4: Residential walk-up apartment floor plan



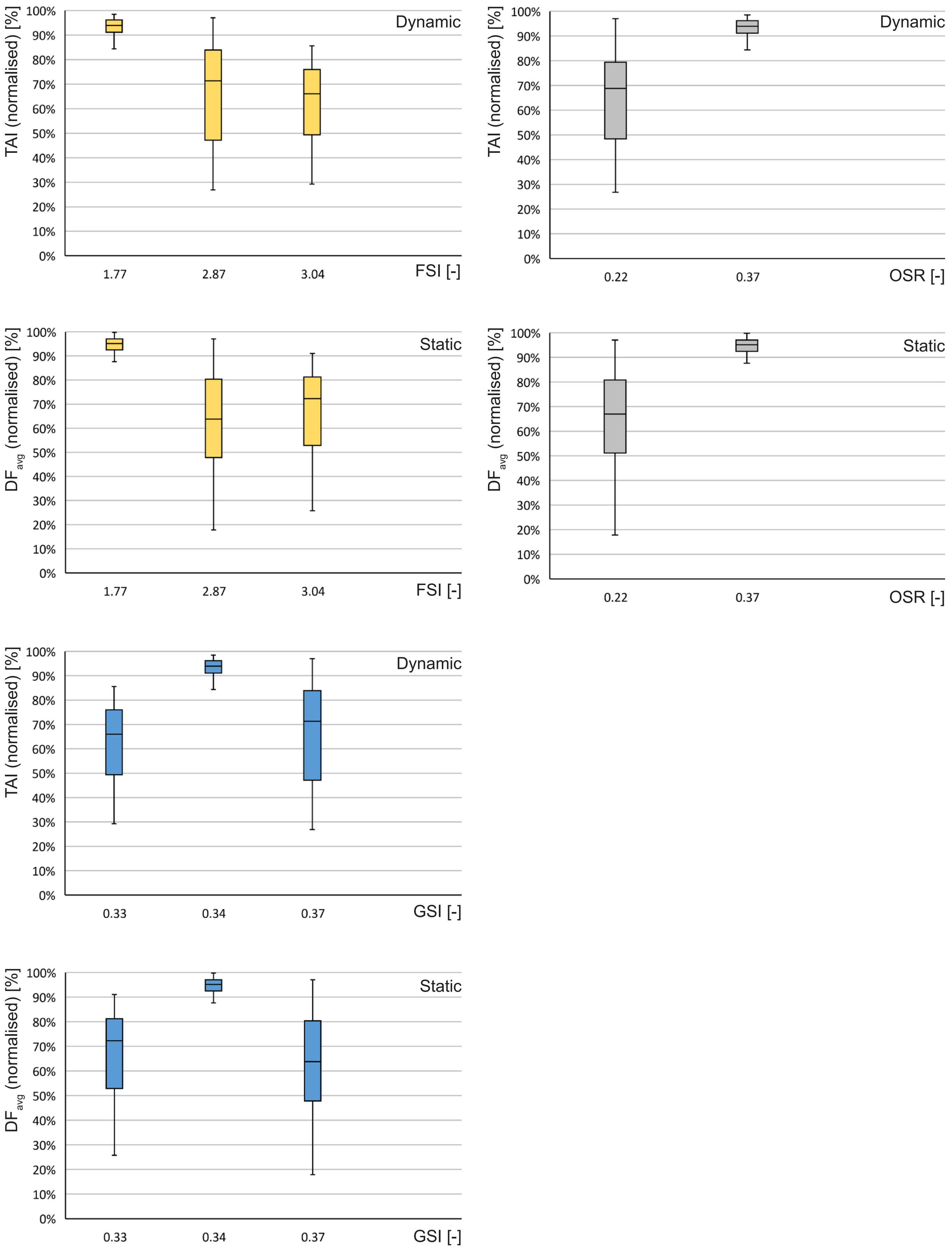
Appendix 5: glazing system properties

	layer	IGDB ID	manufacturer	specification	thickness	reflectance value		transmission value	
						V(λ)	M(λ)	V(λ)	M(λ)
triple glazing system, thesis standard	1	4157	Pilkington	Suncool 50/25	6*				
	2	9	N/A	argon 90%	12				
	3	16682	Pilkington	Optitherm s3	4*				
	4	9	N/A	argon 90%	12				
	5	4116	Pilkington	Optifloat clear	4				
					Total	19.3	?	42.8	?
triple glazing system	1	4135	Pilkington	Suncool 60/31	6*				
	2	9	N/A	argon 90%	12				
	3	16682	Pilkington	Optitherm s3	4*				
	4	9	N/A	argon 90%	12				
	5	4116	Pilkington	Optifloat clear	4				
					Total	37.4	?	53.2	?
double glazing system, low SHGC	1	4542	AGC	Energy 65/42S	6*				
	2	9	N/A	argon 90%	16				
	3	4342	AGC	Planibel Clearvision	4				
					Total	26.1	?	65.6	?
double glazing system, high transmission	1	4342	AGC	Planibel Clearvision	4				
	2	9	N/A	argon 90%	16				
	3	4553	AGC	iplus 1.0	*4				
					Total	20.6	?	71.4	?

Appendix 6: (building floors <= 10)

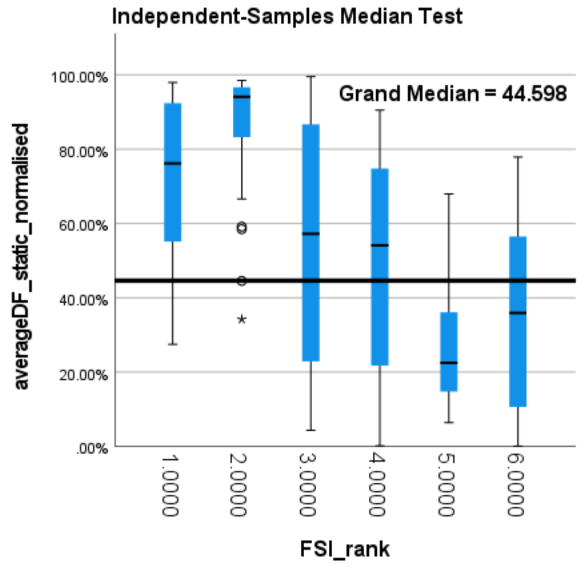


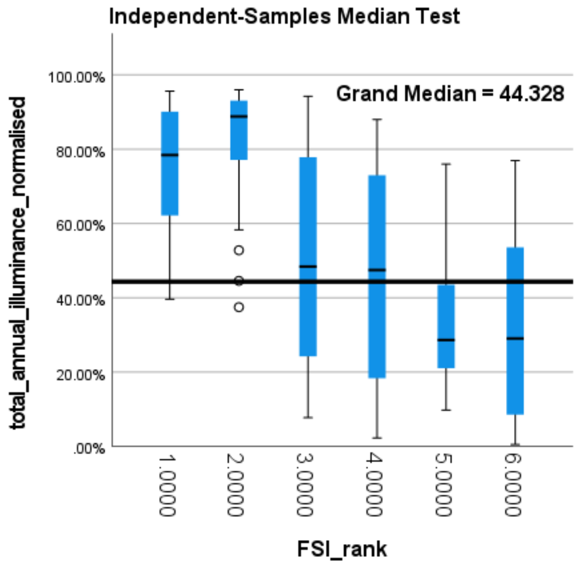
Appendix 7: (building floors ≥ 11)

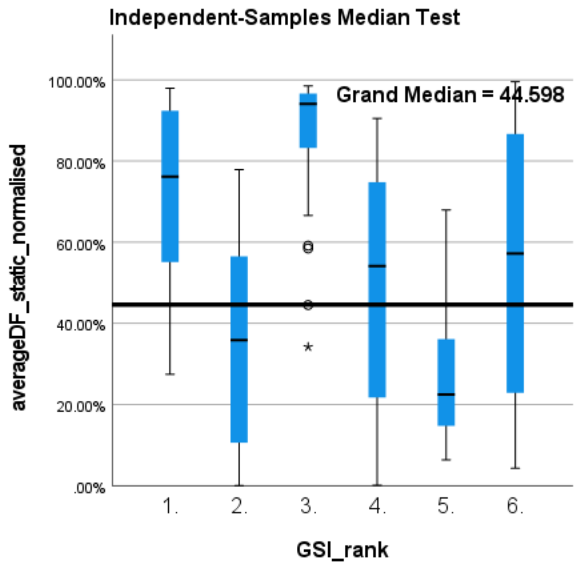


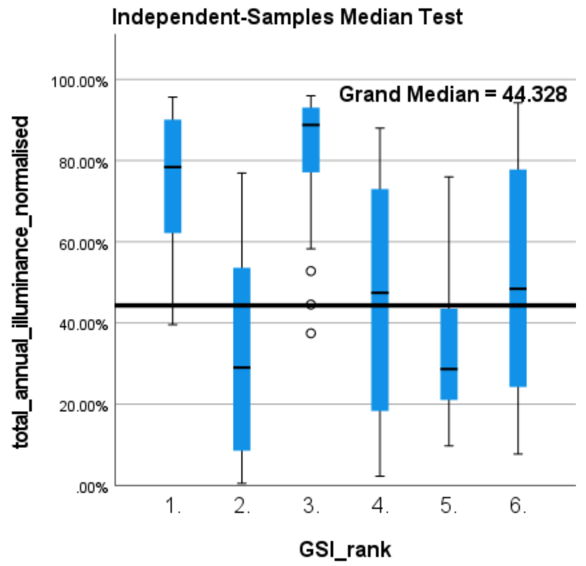
Appendix 8: Statistics on FSI and performance

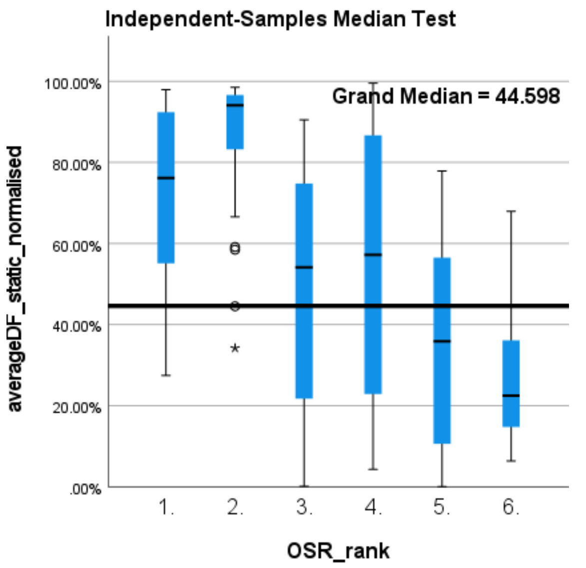
Building floors <= 10

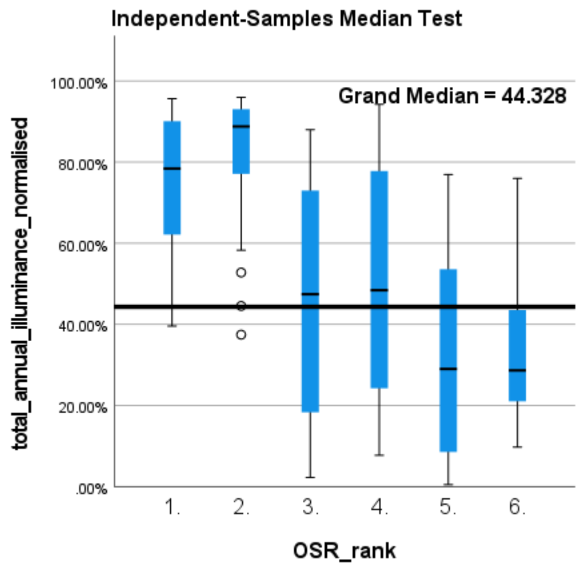




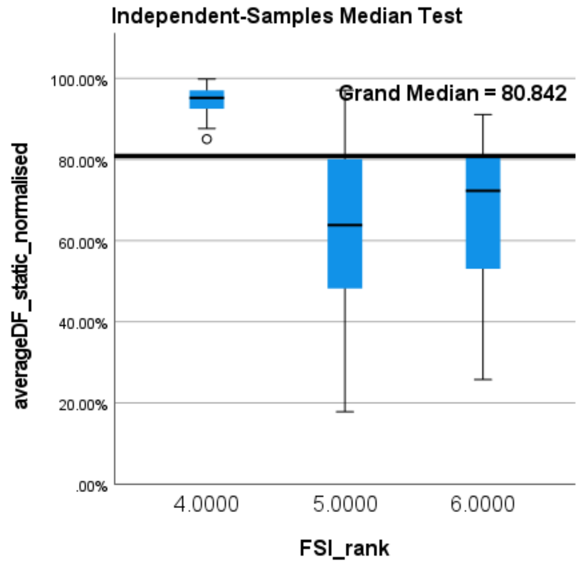


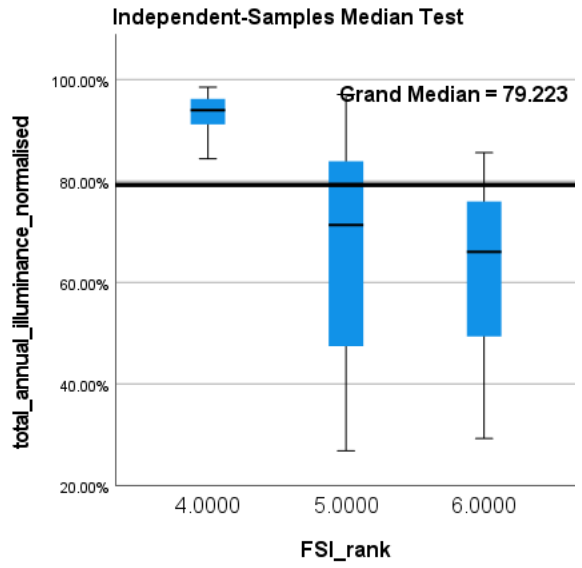


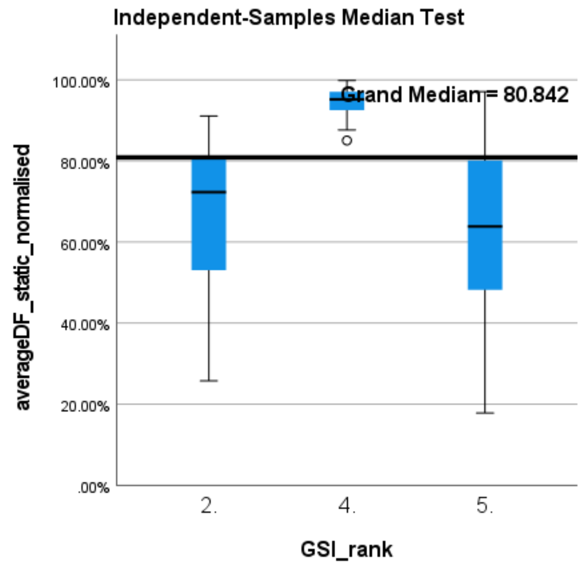


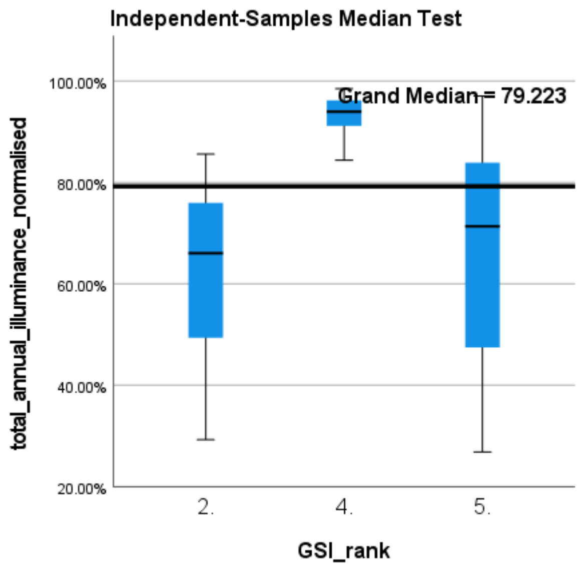


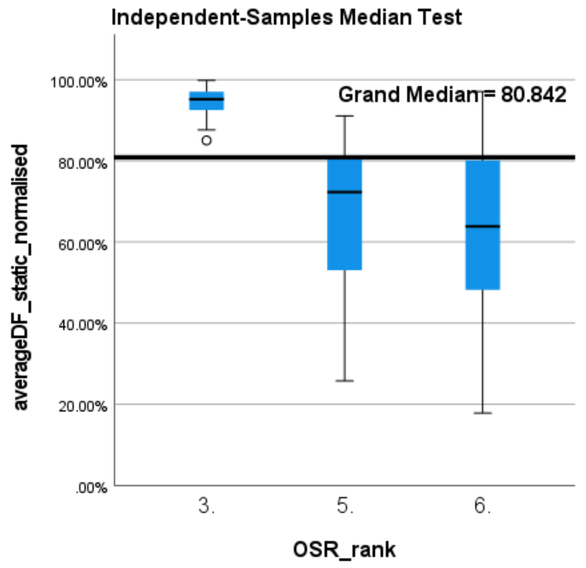
Building floors ≥ 11

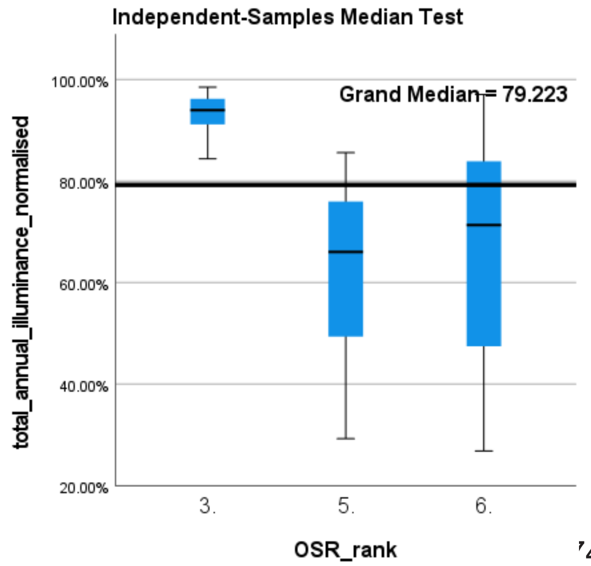












Appendix 9: SVF as a function of building floor (all results)

Mean sky view factor (SVF) as a function of building floor, for all simulation results. Error bars represent +/- 2 standard deviations, meaning 75% of the results are likely to fall within this range (Chebychev's theorem, 1867).