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The effect of urban density on compliance with indoor visual and non-visual daylight targets: A Dutch case study

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ABSTRACT

The high density of the urban fabric poses a real challenge for adequate daylight design in residential buildings. European and national building standards do not provide sufficient guidelines on if and how to consider the urban context at design stage. This study assessed the impact of simulating different urban densities on the indoor daylight performance of typical Dutch apartments. Results showed that not including the surrounding environment when designing a new building leads up to an 85% overestimation of daylight performance, causing an insufficient daylight provision for most apartments built at the lower floors. Furthermore, settling for daylight target values any lower than the minimum standards specified by EN17037 (median illuminance of 300 lx) will lead to insufficient melanopic light levels. In this regard, two new metrics are introduced to compare the non-visual performance between apartments: Melanopic Autonomy and Melanopic Isotropy. These metrics enable the characterisation of non-visual performance of an entire space, rather than of a single occupant position. Last, the analysis explored the relationship between indoor daylight performance and urban density indicators; while the results are limited to the sample considered in this study, a promising relation was noticed for the floor-space index and for the open-space ratio.

1. Introduction

Daylight is a fundamental necessity for any space that strives to provide comfort and wellbeing to its occupants (Knoop et al., 2020). A sufficient level of daylight is needed throughout the day to maintain healthy circadian rhythms and to save energy from the usage of electric lighting. Several studies demonstrated that urban morphology can have a strong impact on the availability of indoor daylight and, consequently, on electric lighting consumption (Pisello et al., 2014; Wang et al., 2021). Yet, the urban form of contemporary cities is often at odd with these basic requirements, due to the increasing density and proximity of buildings, and to the more stringent energy requirements that dictate the use of smaller apertures (Lee et al., 2022). Such high-density cities further exacerbate inequalities by reserving apartments with excellent daylight levels and view out – sold at a premium cost – to the wealthy segment of the population, while apartments that can be afforded by the majority of people are often those with poor access to daylight and view (Zielinska-Dabkowska & Xavia, 2019).

Yet, building regulations and standards focus mainly on indoor performance and often do not include precise guidelines on the inclusion of outdoor obstructions in the evaluation method. Complete and accurate modelling of urban elements surrounding a building is undoubtedly challenging; Strømann-Andersen and Sattrup (2011) highlighted the importance of assigning accurate reflectance properties to the urban geometry surrounding the analysed building, in order to perform reliable energy and daylight evaluations; Pantazatou et al. (2023) analysed the input required from a semantic city model to obtain precise daylight factor results and found that using an LOD2.2 (i.e., Level of Detail – a codified description of geometrical accuracy and completeness of city models), as well as modelling protruding balconies, was an important factor. City models with such a high definition are however not available for all locations and countries; on top of this, the computational effort required to run daylight simulations that include accurate geometries of urban areas is substantial.

As an alternative, the provision of evidence-based performance decrease factors could enable simple and effective quantification of the adverse effects of urban density on visual and non-visual benefits provided by daylight. Li et al. (2006) found an inverse correlation between the angle of obstruction and the Daylight Factor (DF) when investigating the urban context of Hong Kong. Xia and Li (2023) investigated the relationship between urban morphology and indoor daylight using simulation and found an inverse correlation between the Floor Area Ratio (equivalent to the Floor-Space Index as defined in this paper) and the DF. Chokhachian et al. (2020) found a similar

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correlation with Floor Area Ratio but the metric used to quantify daylight performance accounted only for direct sunlight access at a specific moment in time (January 17). Bournas (2020) analysed thousands of residential rooms in the Swedish context and found a relationship between the Vertical Sky Component (VSC) and the Glass To Floor ratio (GTF) with the frequency of compliance with national and European norms. They also found a good correlation between the Useful Daylight Illuminance (UDI) metric and urban density, defined as the ratio between the volume of buildings present in a certain area over the surface of that same area (in m^3/m^2). As found in an extensive literature review on thermal and visual comfort indicators for high rise buildings (Caswell et al., 2024), older studies mostly used the DF metric – which evaluates daylight level in the 'worst-case' condition of an overcast sky – while newer studies introduced correlations between urban forms and climate-based daylight metrics – often spatial Daylight Autonomy (sDA) – that make use of data from weather files for annual evaluations.

Daylight is essential for its effects on human health and wellbeing, beside the visual effects referred to by the majority of standards and regulations. The role of windows in buildings as an interface and connection to the outdoors cannot just be replaced by electric lighting due to the multi-faceted impact that such connection have on human psychology and physiology. In densely built urban contexts and modern 'indoorsy' lifestyle, a connection to the outdoor environment is arguably even more important than in rural areas but it is not yet codified in building regulations, thus not influencing design. To the authors' knowledge, only two studies added considerations on the effect of the urban form on non-visual (also called non-image-forming) metrics, i.e., metrics that aim to quantify the influence of daylight on humans' circadian rhythms. The first of these studies focused on the sensitivity of non-visual evaluations to the spectral characterisation of the sky, and included a parametric analysis of outdoor obstructions as a factor that influences the redistribution of daylight spectral properties (Diakite-Kortlever & Knoop, 2022). The second one presented a parametric analysis of urban canyons and their effect on indoor non-visual metrics for a simplified scenario; findings showed that the spectral properties of urban surroundings become more relevant for non-visual evaluations in dense urban contexts and in the presence of small Window-to-Wall Ratio (WWR), i.e., lower sky view factors (Šprah et al., 2024).

The present work investigates compliance with national and European norms for residential apartments in the context of Dutch dense cities. Furthermore, it includes novel considerations on how urban density in existing cities affects non-visual effects of daylight, quantified with methods prescribed by building certification guidelines and expressed with two new metrics (Melanopic Autonomy and Melanopic Isotropy) that emphasise the spatial character of light non-visual performance.

1.1. Densifying cities: the case of The Netherlands

There is a large demand for housing in the Netherlands: the population is growing (CBS, 2022), life expectancy is ever increasing (CBS, 2021) as is the average size of a household (CBS, 2022). This is causing the inability to move house for many people, while at the same time rental rates and mortgages are at an all-time high, resulting in unaffordable housing and negative consequences on society and our built environment (CBS, 2022). To tackle these problems, the Dutch Ministry of the Interior and Kingdom Relations (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties) plans to build 1 million homes before 2030, of which 50% will be built in the provinces of North and South Holland (Ministry of Housing and Spatial order, 2022). To accommodate the construction of these houses, city densities are likely to increase as well as the average building height.

1.2. National and European daylight provision targets

Currently, Dutch building regulations (Besluit bouwwerken leefomgeving – BBL 2024) rely on the NEN 2057 methodology to assess the minimum daylight levels required in buildings. Such requirement prescribes a minimum aperture area equivalent to 10% of the floor area for residential spaces in new buildings. The calculation of the aperture area needs to be corrected for potential outdoor obstructions, overhangs and balustrades, following a method based on planar angles and simplified geometries; however, regulations prescribe such corrections just for the obstructions within the plot of the building under analysis, without taking into account existing buildings around it (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2024; Nederlandse Norm, 2011).

Meanwhile, the most recent European standard for daylight in buildings, EN 17037:2018, introduced significant advances in daylight evaluation methods, proposing climate-dependent targets and sDA as an alternative approach (Method 2 in the norm) opposed to the more standard calculation of DF proposed in Method 1 (European Committee for Standardization, 2018). Although the inclusion of significant outdoor obstructions is mentioned in the norm, there is no defined method to retrieve geometrical and optical data from urban environments. A few studies analysed the effect of this norm on daylight design in different European countries; it was generally found that the suggested minimum daylight levels are significantly higher than the current national requirements for Estonia, Sweden and Slovenia, and that by using Method 1, based on the DF metric, it is harder to achieve compliance than by using Method 2, based on climate-based metrics (Bournas, 2020; De Luca & Sepúlveda, 2021; Hraška & Čurpek, 2024; Ticleanu et al., 2023).

Dutch building regulations are expected to adopt the EN 17037 method in the near future and to express compliance targets as DF values. This change will lead to more accurate, performance-based daylight requirements, as well as favouring a better integration with other European countries and building certifications such as LEED (US Green Building Council (USGBC), 2013), BREEAM (Building Research Establishment, 2022) and WELL (International WELL Building Institute (IWBI), 2016). There is, however, still a debate on which target DF values to adopt, given the difficulty in reaching the European norm targets for dense cities. For The Netherlands (Amsterdam), the EN 17037 norm suggests a minimum DF of 2.1% for 50% of the floor area (per "space") and a minimum DF of 0.7% for 95% of the space. The latest proposal for the implementation of the norm in the BBL suggests instead a single target DF of 1% for 50% of the space, which matches more closely the current requirements for residential buildings (NEN-commissie Daglicht, 2021).

1.3. Melanopic targets

Non-visual daylighting requirements are relatively new and only implemented in building design guidelines since the introduction of the circadian requirement in the WELL certification (International WELL Building Institute (IWBI), 2016). Such requirement is based on medical research on the melanopsin receptors' sensitivity to light (Al Enezi et al., 2011; Lucas et al., 2014) and on the CIE Standard S 026:2018 that defines the metric Melanopic Equivalent Daylight Illuminance (M-EDI), representing the illuminance of standard daylight (D65) required to achieve an equivalent melanopic irradiance (CIE Division 6, 2018, 2023). Within the WELL certification guidelines, 136 M-EDI are necessary to obtain one credit (sufficient performance) and 250 M-EDI are necessary to obtain three credits (optimal performance), measured on a vertical plane at eye level.

To summarise, this paper aims to quantify the decrease in daylight availability, with its related visual and non-visual effects, when urban contexts with varying density are taken into account in the evaluation. Compared to previous work, here the emphasis is on the implications

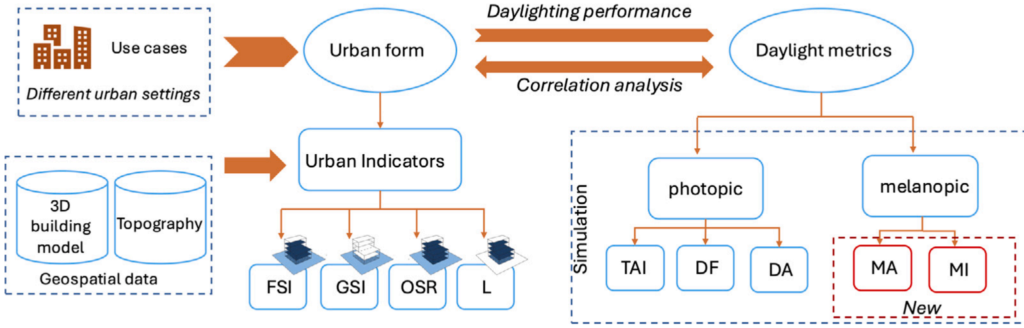

Fig. 1. Methodological framework describing the approach adopted in this work.

that current building norms and standards have on the expected daylight performance in dense urban cities. The analysis focuses on the likelihood that standard apartment units reach the thresholds required by the current standards even in the presence of external obstructions. Novel metrics to convey the spatial character of non-visual daylight performance are introduced. The work aims at achieving the following three objectives: (1) quantify the reduction in indoor daylight performance caused by modelling the urban context at design stage; (2) evaluate whether apartments that comply with minimum photopic targets are able to achieve melanopic targets; and (3) identify urban indicators that can potentially be used as a proxy for estimating indoor daylight access over large urban areas.

2. Methodology

To quantify the effect of urban form on daylight target, the first step was to select case study cities that well represent different densities and urban contexts typical of The Netherlands and find reliable data on their characteristics (Sections 2.1 and 2.2); next to that, standard apartment configurations that comply with building regulation were defined (Section 2.3). To quantify indoor daylight performance, metrics were chosen for their use in standards and certifications (average DF, average and spatial DA) or because they can represent climate-based performance on a continuous, non-percentage scale that better suits statistical and regression analyses (average TAI). The simulation workflow built for the analysis is presented in Section 2.4. Last, two new metrics (Melanopic Autonomy and Melanopic Isotropy) had to be introduced to quantify the melanopic performance across the apartment spaces with single numerical values and to allow comparison between all analysed cases. Such new metrics are defined in Section 2.5. The framework of the overall approach followed for this work is summarised in Fig. 1.

2.1. Urban data

The geometry of the urban context is derived from openly available 3D building models of the Netherlands (LOD2), published by TUDelft3D. The geometry data (see an example in Fig. 2) is a combination of point cloud data from AHN (National Height Model of the Netherlands) and BAG (Register of Addresses and Buildings), used to create 3D geometry (Peters et al., 2022).

To include ground 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 open database is an authorised large-scale digital map which contains detailed information on all landscape elements in the Netherlands, e.g., trees, street lighting and more. In this work, layers 'Water area', 'Unclassified water area' and 'Overgrown area' are used to import all relevant patches in the model.

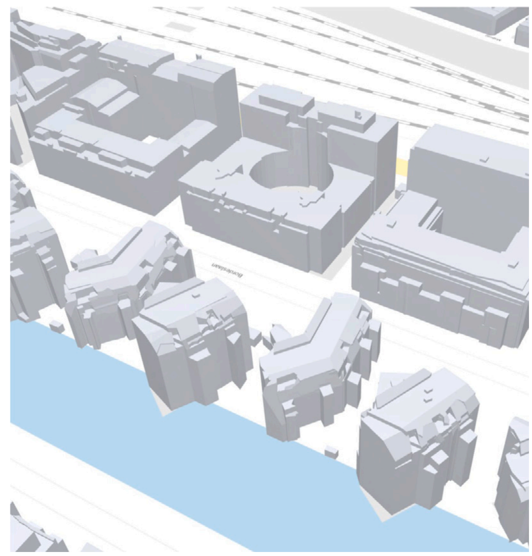

Fig. 2. Example output of geometry from 3D BAG. The location is Paleiskwartier in 's-Hertogenbosch.

2.2. Urban fabric indexes

Berghauser-Pont and Haupt (2007) described urban density with four main indicators and graphically summarised this in a graph, called Spacemate, that can help in describing performance differences in urban areas with distinctive characteristics. The four indicators are: the floor-space index (FSI), the ground-space index (GSI), the open-space ratio (OSR) and average layers (L). The definitions of these metrics are shown in Fig. 3. For the present work, the values of such indicators were retrieved from the RUDIFUN database (PBL, 2022), focusing on the gross (i.e. inclusive of public areas) building block and neighbourhood scales.

For the selection of the six case study areas, the urban indicators were visualised in QGIS (2023) and used to identify areas with a relatively homogeneous density (Fig. 4). This removed possible bias where one side of a building can be much less dense than the other, confounding simulation results. The Amsterdam Zuidas district and the Rotterdam Maritime district were selected as areas among the ones with the highest urban density. Using filtering queries in QGIS, an urban patch in Eindhoven and the Utrecht city centre were selected as areas with a medium density, while the Delft Voorhof district and Rotterdam North were selected as areas with a low density. Any area with a FSI lower than 1.00 was excluded from this study as not considered part of the urban fabric and was expected to have no context-related issues with daylight. After the six suitable locations were identified, a building block was chosen and replaced with a standard residential building

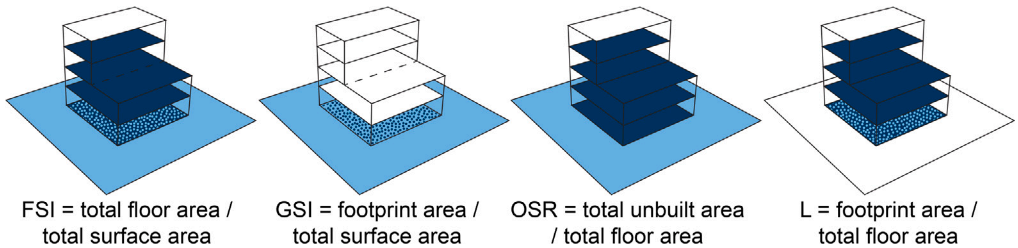

Fig. 3. Definition of the four urban density indicators used in this study to select urban areas and to test correlations with daylight metrics.

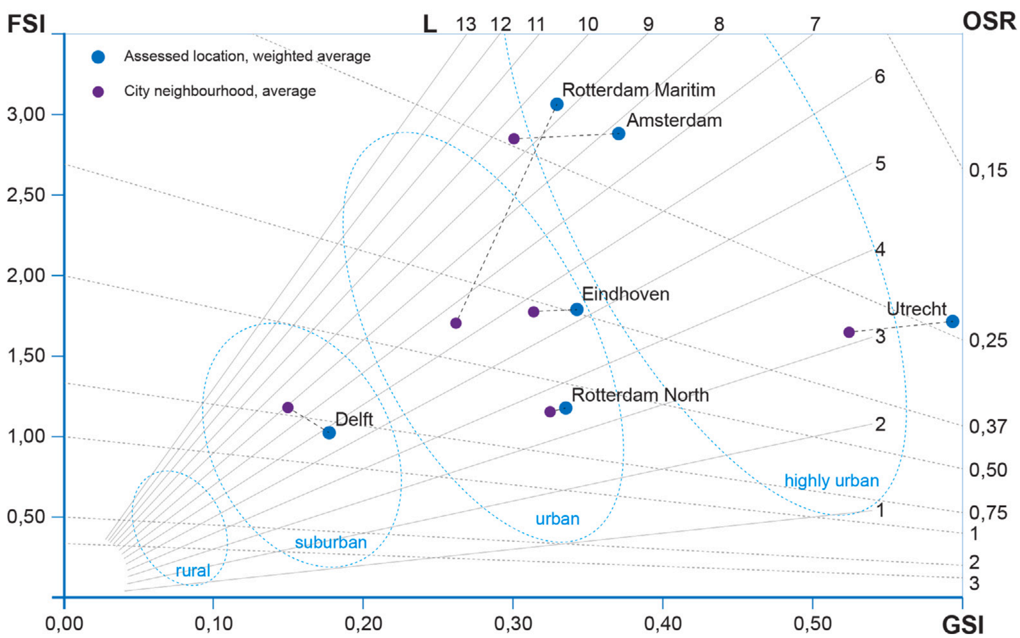

Fig. 4. The Spacemate graph with the assessed locations and their grade of urbanisation. GSI and FSI are represented on the X axis and on the Y axis respectively. OSR and L values further subdivide the space with two more coordinate systems.

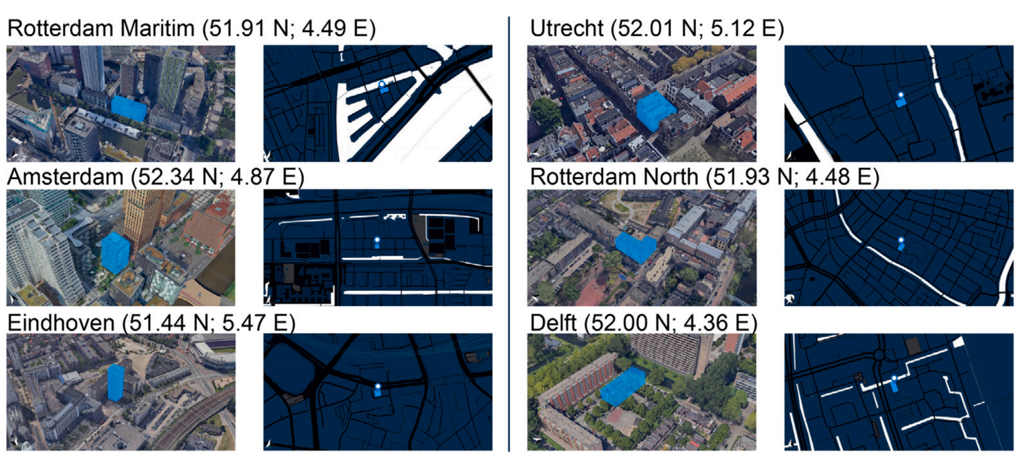

Fig. 5. Location of the six urban areas assessed in this study, in 3D and planar view. The buildings highlighted in light blue were replaced with the standard residential buildings used in this work. In the planar views, water bodies are indicated in white and roads are indicated in black. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(described in the next section) to assess its daylighting performance. The final locations are shown in Fig. 5.

One of the objectives of this work was to find correlations between urban density indices and indoor daylight performance, potentially leading to a set of performance decrease factors that can be used in large-scale, national evaluations. Hence inferential statistic methods were preferred over other types of statistics. Two initial tests were performed towards this aim: an independent-samples median test and a Kruskal–Wallis H test (also known as a one-way ANOVA on ranks test). In the first test, results show if there are two or more homogeneous subsets that have comparable mean values to the dataset. In this study, the different cities represent independent samples (nominal, n=6); the median of each sample is compared to the grand median of all results (ordinal). Since the used dataset has no known distribution (i.e., is not

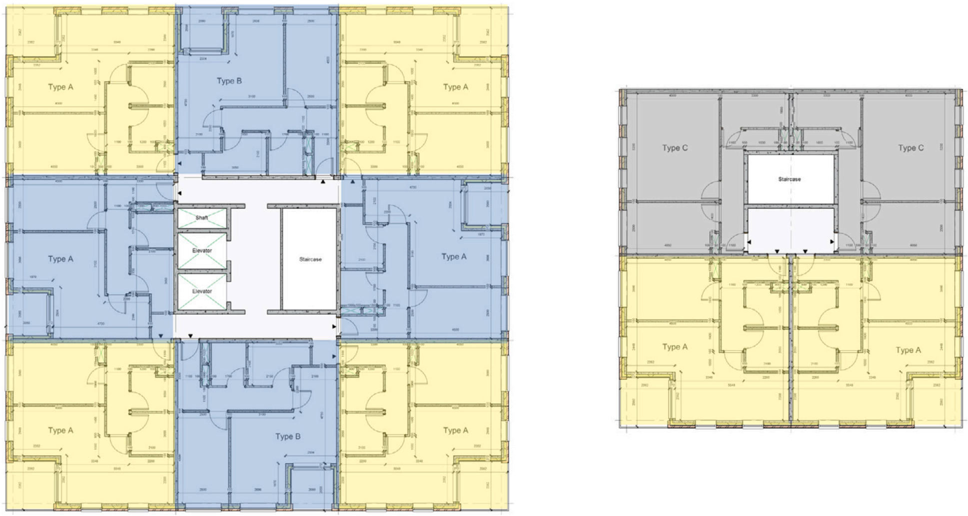

Fig. 6. Internal layout of the tower block (left) and of the walk-up apartment building (right). Type A apartments are coloured in yellow, Type B apartments in blue and Type C apartments in grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

normally distributed) and considering the combination of nominal and ordinal types of data, the choice of a non-parametric test is justified. The second test, a Kruskal–Wallis H test or one-way ANOVA on ranks test, show if there are significant differences in the result distribution of two or more independent groups. This non-parametric test is preferred over the one-way ANOVA test, since it is suited for more than two independent samples whereas the one-way ANOVA test is only suited for two samples (Ostertagová et al., 2014). The test ranks all the results and tests if they correlate with the expectation of rank. The expectation of rank is based on the variable rank (FSI, GSI or OSR in this study). The use of this non-parametric test is justified in this case as well as the dataset has no known distribution. Both tests are assessed using a null hypothesis. The null hypothesis for the first test is that the normalised performance is similar for all sample cities and their urban indicators. The null hypothesis for the second test is that the distribution of the normalised performance results is similar for all samples. Last, a regression analysis between urban indicators and daylight performance was attempted.

2.3. Standard residential buildings

Two standard building designs were assessed in this study. These were defined by the authors to match typical WWR values found in the database of the Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland - RVO) and to meet compliance with BBL 2024 target values. 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 is used in the context of Amsterdam, Rotterdam Maritime and Eindhoven; the walk-up apartment building is used in the context of Delft, Utrecht and Rotterdam North.

The residential tower's floor plan is shown in Fig. 6. The tower consists of eight residences: four double-oriented residences (Type A) and four single-oriented residences (Type B). In total, the tower consists of 23 floors of 3 meters height, for a total height of 69 m. The configuration of the walk-up apartment building (Fig. 6) is similar to the tower's configuration but smaller in size. The building consists of type A residences at the corners and type C residences elsewhere. 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.

To simplify the process and data analysis, the residences are simplified by creating one open space per residence without interior walls.

Table 1
Radiance ambient parameters for all simulations.

	ab	ad	as	ar	aa
Static analysis (DF/M-EDI)	10	4096	2048	1024	0.05
Dynamic analysis (DA/TAI)	10	8192	4096	n.a.	n.a.

The loggia remains identical, and facade properties are kept similar. The average WWR for the simplified apartments are respectively 0.33 (A), 0.60 (B) and 0.48 (C). A comparison analysis made by the authors between the complete layout (used as reference) and the simplified layouts showed that there is a decrease in simulated performance of 3%, 5% and 15% for apartment types A, B and C respectively, when evaluating Total Annual Illumination (TAI), i.e., the cumulative illuminance falling on a horizontal plane over a full year. This difference is within the expected error for daylight simulation (±20%), thus the conclusions drawn for the simplified layouts can be applied to the complete layouts as well.

2.4. Simulation settings

The results from this work are based on simulated performance as a representation of the information available to designers and consultants during the design phase and used towards compliance purposes. Both daylight assessments included in this study (photopic and melanopic) rely on simulation tools to obtain the metrics that are required by current standards and certifications (DF, DA and M-EDI). In this work, the photopic and melanopic indoor performance of the standard apartments was simulated using Ladybug Tools (Roudsari & Pak, 2013) and LARK v2 (Gkaintatzi-Masouti et al., 2022), respectively. Both programs are available as free plugins for Rhinoceros/Grasshopper and they both rely on *Radiance* (Ward Larson et al., 1998) as a light redistribution engine. The characteristic error for point-in-time indicators using *Radiance*-based tools is considered to be ±20% (Brembilla & Mardaljevic, 2019; Pierson et al., 2023). The *Radiance* ambient parameters were set as per Table 1 after performing a convergence test.

Ladybug Tools (more specifically, the Honeybee components) was used to obtain DF (in %), Daylight Autonomy (DA, in %) and Total Annual Illumination (TAI, in klx hr). The simulation run times were optimised by using Accelerad (Jones, 2017, 2019). This software allows Radiance to make parallel computations using the graphical processing unit (GPU). Results from Accelerad were initially verified against a control run using regular Radiance and found to be accurate for DF,

Table 2
Reflectance properties of indoor surfaces.

	Photopic reflectance	Melanopic reflectance
Floor	36%	26%
Walls	63%	54%
Ceiling	88%	88%
Frames	43%	43%

DA and TAI evaluations. All metrics were computed on a horizontal grid placed at a height of 850 mm, with a 200 mm spacing between sensor points and an offset of 500 mm from the walls.

LARK v2 was used to obtain the M-EDI values (in lx). In this case, the grid was set with a spacing of 1000 mm and at a height of 1200 mm, to represent eye level for a seated position. Rather than pointing upward, view vectors were defined on a horizontal plane, looking towards four different directions, orthogonal to the room orientation.

The characterisation of the luminance of sun and sky was defined using irradiance data from the IWEC weather file for Amsterdam and the Perez All-Weather model (US Department of Energy, 2025), which is a widely used approach in simulation of daylight performance and among designers. The IWEC database provides weather files representing typical meteorological conditions for use in building simulation software (Thevenard & Brunger, 2002) and, although outdated, is the most authoritative source of weather data for locations outside of the USA. The Perez All-Weather model (Perez et al., 1993) is an empirical luminance distribution model that directly correlates weather variables such as solar irradiance to the luminance emitted by different portions of the sky; due to the convenience of using it in combination with weather files, it is a widespread model for photopic performance evaluations. For the spectral characterisation within LARK, a standard illuminant D65 spectrum was used for all simulations to represent the typical sky spectral power distribution of mid-latitude regions (Pierson et al., 2022), while the sun was characterised as a white constant light source. Only a few selected days were included in the analysis, as the simulation only allows for point-in-time evaluations and not for annual ones. Clear sky days close to the solstices and equinoxes were selected from the weather file and daily analyses were performed from 7:00 to 17:00 for the following dates (dd/mm): 04/01, 26/03, 07/06, 29/09. Days with a daily average cloud cover fraction lower than 0.2, calculated from weather file data, were classified as clear sky days and selected for the analysis. Clear sky conditions represents instances in which the indoor melanopic daylight performance is at its highest potential and is stable during the day, reducing the uncertainty in the interpretation of results.

Realistic data on material reflectance and transmittance properties are crucial for daylight simulation and for inter-building effects in urban settings (Strømann-Andersen & Sattrup, 2011). Reflectance properties for opaque materials were gathered from SpectralDB and are reported in Table 2 (Jakubiec, 2023). Windows were assumed to be triple-glazed, to represent high-performing glazing that is likely to be installed in new buildings, with a transmittance of 42.8% and a reflectance of 19.3%; data were gathered from LBNL Window 7.8 (Curcija et al., 2015).

For outdoor material properties, the same databases were used, but overall building reflectance was calculated as a weighted average between opaque and transparent surfaces. The choice of opaque material, window type and WWR was dictated by the building type and construction year, as found in the RVO database. Ground reflectance values were assigned based on the surface classification found in the BGT database: paved surfaces were assigned a reflectance of 18%, green areas a reflectance of 25% and water bodies a reflectance of 10%. Trees, small urban elements and terrain levels were not included in the simulation model since they might vary their properties over time and do not significantly influence the results.

2.5. New metrics: Melanopic Autonomy and Melanopic Isotropy

The non-visual daylight performance of the apartment units had to be expressed with aggregate indicators to allow for a straightforward comparison between all the different situations. Using a single point in the middle of the apartments as suggested by the WELL certification could produce biased results due to local effects, such as partial shadows. In this work, the authors introduce two new metrics to communicate the spatial performance of melanopic illuminance: Melanopic Autonomy (MA) and Melanopic Isotropy (MI), respectively used to assess the intensity of melanopic illuminance and the 'flexibility' in view direction for sufficient melanopic exposure. For both metrics, a higher percentage is more favourable. Melanopic Autonomy is defined as the percentage area that has at least one view direction that fulfils a certain requirement (here set at 250 M-EDI). Melanopic Isotropy is defined as the total percentage of vectors that fulfil melanopic requirements. In other words, in a room with a MI percentage of 100%, one receives enough melanopic stimulus in all view directions. For the scope of this paper, the combination of MA and MI was considered sufficient to express the melanopic performance of any room. Fig. 7 shows an example of how the two metrics are calculated for a fictitious room.

3. Results

The first part of the results shows the difference in photopic performance when the urban context is modelled and when not. The second part presents results of the melanopic illuminance analysis and the third part is dedicated to the relationship between indoor performance metrics and urban indicators.

3.1. Impact of modelling the urban context

The baseline for this analysis is the indoor daylight performance of the selected apartments without any urban context modelled around them. Fig. 8 shows DF results for the main apartment rooms and for the overall performance of the simplified apartment layouts (i.e., layouts with no internal partitions, which will be used for all further analyses). Apartment A, which has two sides with windows, easily complies with the EN 17037 targets for the minimum median DF (corresponding to 2.1% for the Netherlands) and for the minimum DF over 95% of the space (DF=0.7%), as well as with the proposed requirements for the Dutch building regulations (median DF=1%, indicated as $BBL_{50\%}$ in the Figure). Apartments B and C do not comply with the median DF targets but do comply with the BBL median target.

Fig. 9 shows the median results for the same apartment configuration but obtained using the DA metric, as per Method 2 in the EN 17037. As already found in the literature, using Method 2 leads to higher compliance rates than using Method 1. In this case, all apartments – in all orientations – meet EN and BBL minimum targets, and apartment A even exceeds the high performance targets. Based on existing literature, results for the 95th percentile are expected to meet the minimum target of 300 lx as well.

The two simplified floor layouts – one for the five-floors walk-up blocks and one for the 23-floors tower – were then re-evaluated when placed in the urban context of the six areas chosen for this study: Amsterdam, Rotterdam Maritim and Eindhoven for the tower (184 apartments per area); Utrecht, Rotterdam North and Delft for the walk-up block (30–40 apartments per area). Fig. 10 shows the aggregate results for all apartments in each area, for both the DF and the DA metrics. The large majority of the apartments does not meet the DF target of 2.1% on 50% of the indoor space. When considering the DA minimum requirement of 300 lx on 50% of the indoor space, more than half of the apartments located in Eindhoven, Rotterdam North and Delft can reach a compliant level; on the other hand, for the urban areas of Amsterdam, Rotterdam Maritim and Utrecht, meeting compliance is not possible for most apartment types, floors and orientations.

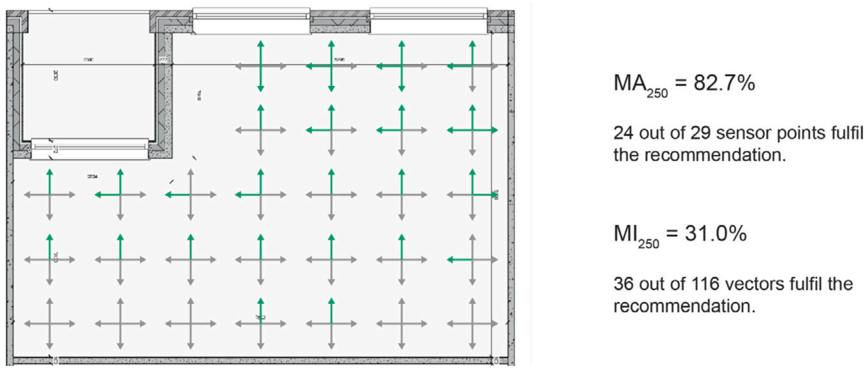

Fig. 7. Example of the calculation for Melanopic Autonomy and Melanopic Isotropy, on a fictitious room and with fictitious results. The green arrows indicate the view directions for which a certain melanopic illuminance recommendation is met. Melanopic Autonomy represents the ratio of complying points and Melanopic Isotropy represents the ratio of complying view directions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

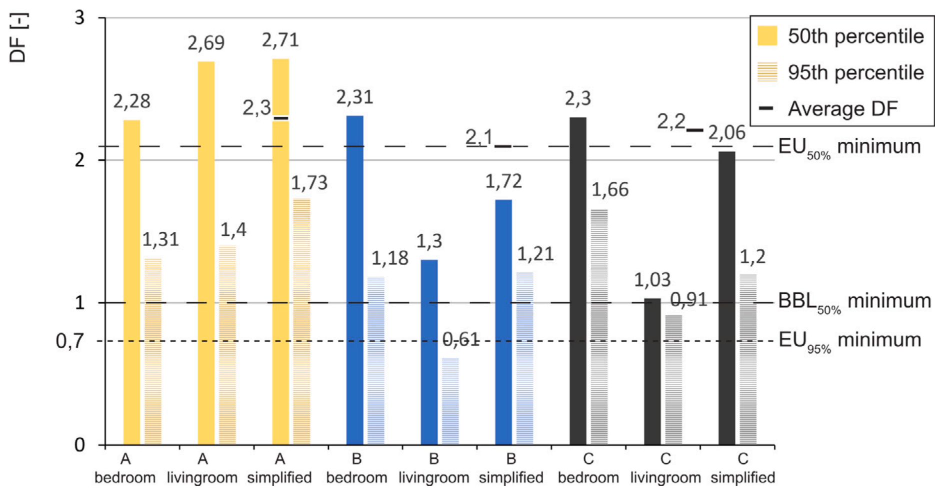

Fig. 8. Static daylight performance (Daylight Factor) for the three apartment types when facing eight different orientations, for both their detailed and simplified internal layouts. The solid coloured bars show the median performance and the hatched bars show the 95th percentile performance.

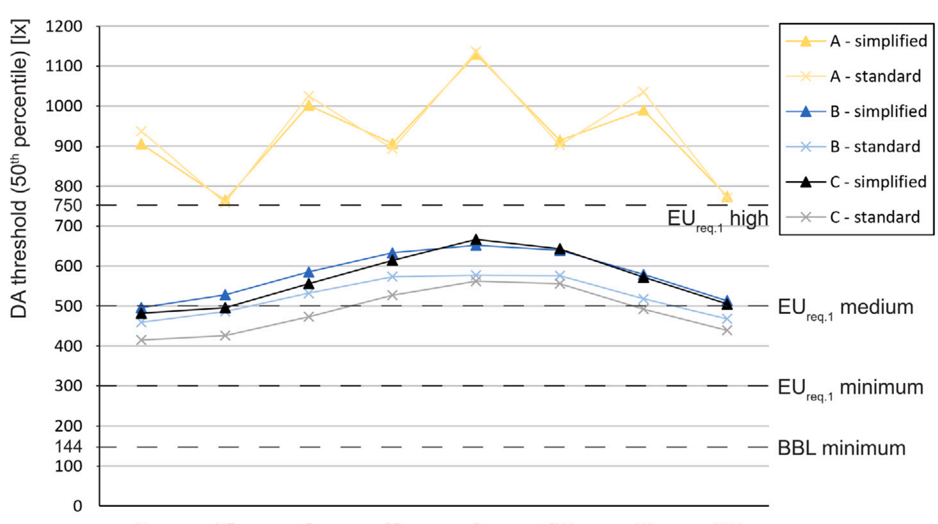

Fig. 9. Climate-based daylight performance (Daylight Autonomy) for the three apartment types when facing eight different orientations, for both their detailed (cross markers) and simplified (triangle markers) internal layouts. The markers indicate the illuminance levels reached on at least 50% of the apartment area. Target values as per EN 17037 and BBL proposal are indicated with dashed lines.

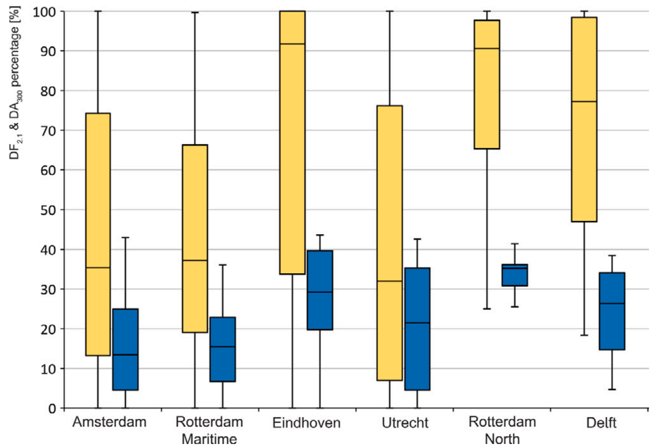

Fig. 10. Static (in blue) and climate-based (in yellow) performance for all apartment types, orientations and floors, aggregated per city and shown as boxplots with whiskers set at the 1.5IQR. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

When including the urban context and quantifying indoor daylight performance again, a drop in performance level is to be expected, due to the increase in outdoor obstructions to daylight access. Such performance drop – calculated relatively to the performance of an unobstructed top floor – is shown in Figs. 11 and 12, for the walk-up apartment configuration and for the tower configuration, respectively. Indoor daylight performance is expressed here in terms of average DF and average TAI, so that results could be normalised against the control scenario with no obstructions. Besides being averaged per layout type, the results are averaged across the eight different compass orientations, which are characterised by different results even for the DF (a metric that is normally independent of the orientation) because of variations in the obstruction elements on the different sides of the building. It can be noticed that the floor-dependency decrease in performance is different depending on the city, both in terms of floor height at which the decrease starts and in terms of the rate at which the decrease change by floor. For walk-up apartments (Fig. 11), the city of Utrecht is the one with the strongest and more rapid decrease in performance, noticeable already at the fourth floor and reaching a 85% decrease in average DF and TAI for the ground floor, compared to a situation in which the urban context is not modelled. For the areas of Delft and Rotterdam North, the decrease is much less pronounced and the difference per floor less noticeable. For tower blocks with 23 floors (Fig. 12), the performance decrease is most pronounced for Eindhoven, where apartments at the highest floors almost reach the same performance as unobstructed apartments but this drops starting from the 11th floor and below, down to 28% of the reference daylight performance. Both Amsterdam and Rotterdam Maritime have a similar drop, from the 70%–80% range to the 10%–20% range, but at different rates per floor, with the performance for Rotterdam dropping more suddenly below the seventh floor and the performance for Amsterdam decreasing gradually. This behaviour is noticeable for both the DF and TAI metrics (shown in Appendix), i.e., for both static and climate-based daylight evaluations.

Relating such results back to the Spacemate diagram in Fig. 4, it can be noticed that the areas with the lowest FSI and OSR (Delft and Rotterdam North) are the ones with the smallest inequalities between daylight performance at the ground floor and at the top floor. Utrecht, the city with the highest urban density indicators, is also the one characterised by the highest difference in daylight access between ground and top floors. Amsterdam and Rotterdam Maritim have a comparable difference in performance between ground and top floors but different change rates; by looking at the Spacemate, this can be explained by the different urban characteristics for the Rotterdam Maritim area of analysis and its immediate surroundings: the first is characterised by a highly urban context while the second is less densely urbanised. In contrast, the area selected in Amsterdam and its surrounding neighbourhood are much more homogeneous. The height and form of the urban 'podium', i.e., the average building height over a certain area, is likely to have an effect on the floor height where the drop in performance is noticeable, as well as on the rate of performance decrease, although this was not further investigated here.

Table 3
Apartments selected for further evaluation on melanopic performance, with their orientation and photopic performance results (compliant with minimum EN 17037 targets).

Orientation	Floor	DA300	DF2.1
North	20	50%	26%
East	23	50%	23%
South	23	46%	22%
West	9	33%	21%

Table 4
Apartments selected for further evaluation on melanopic performance, with their orientation and photopic performance results (compliant with proposed BBL targets).

Orientation	Floor	DA144	DF1
North	0	56%	31%
East	6	71%	41%
South	12	50%	17%
West	7	62%	34%

3.2. Melanopic performance in urban contexts

For the assessment of melanopic performance, the analysis was restricted to a few selected apartments that just meet the photopic performance targets as described before. For apartments that are performing really well or really poorly, it is expected that melanopic performance will have the same trend of the photopic one. Instead, for apartments that just comply with guidelines and building regulations, it is important to understand whether melanopic performance can be met too. Type B (side-lit) apartments of the tower block in Rotterdam Maritim location were selected as at least one apartment met EN 17037 and BBL minimum targets using Method 2 in almost each orientation (except for the South one). For each orientation, the apartment placed at the floor that first met requirements was selected for the melanopic assessment. Tables 3 and 4 indicate the floor at which apartments complying with photopic requirements (EN Method 2, target values of 300 lx and 144 lx respectively) are located and their performance value in terms of DA and DF.

For these eight selected apartments, melanopic performance was simulated across the apartments and melanopic autonomy (with a target value of 250 M-EDI) was calculated from the punctual results. The analysis was performed for the closest clear sky days (as found in the weather file) to equinoxes and solstices. This choice allows to show the potential indoor performance in the best possible outdoor conditions throughout the year. Fig. 13 shows the results on such dates for apartments complying with the median DA300 requirement (left column) and with the median DA144 requirement (right column). The first set shows a generally good melanopic performance, with the MA250 target being met across the entire apartments for most of the day. The performance in winter is obviously lower (with the East side being the most affected one, mostly because of site-dependent external obstructions), but this is to be expected because of the winter shorter days. On the other hand, for the second set of results (DA144, right column), the melanopic performance is more unstable throughout the year and during the same day, with the East side being again the one that is mostly affected by the low daylight levels caused by outdoor obstructions. In this specific context, for apartments facing East, in full winter, only a maximum of 18% of their indoor space receives sufficient light to provide a good circadian entrainment.

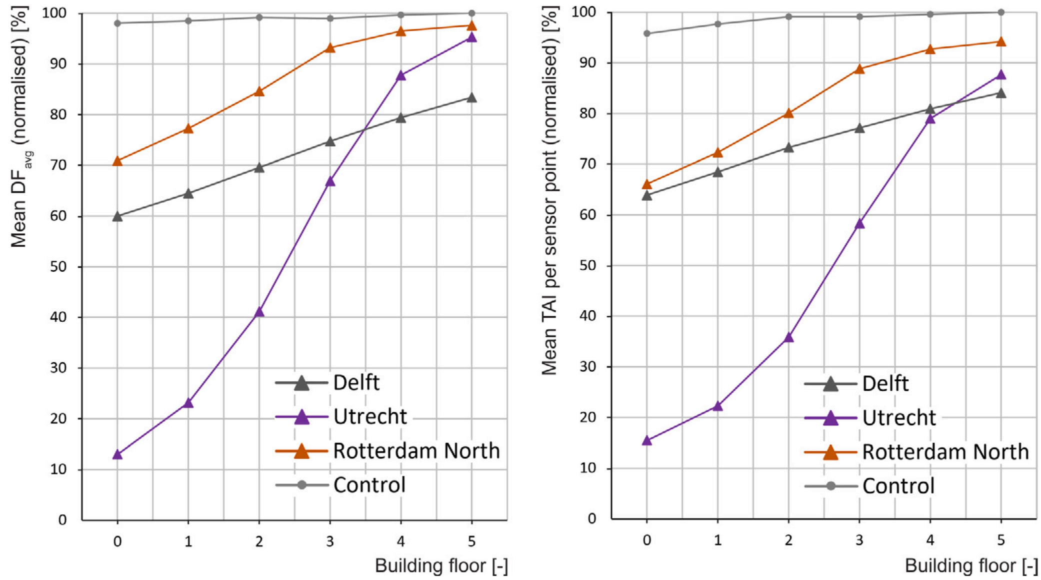

Fig. 11. Static (left) and climate-based (right) performance of the walk-up apartments, shown per floor and per city. Results are normalised against the performance of an unobstructed building of the same type and averaged over different orientations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

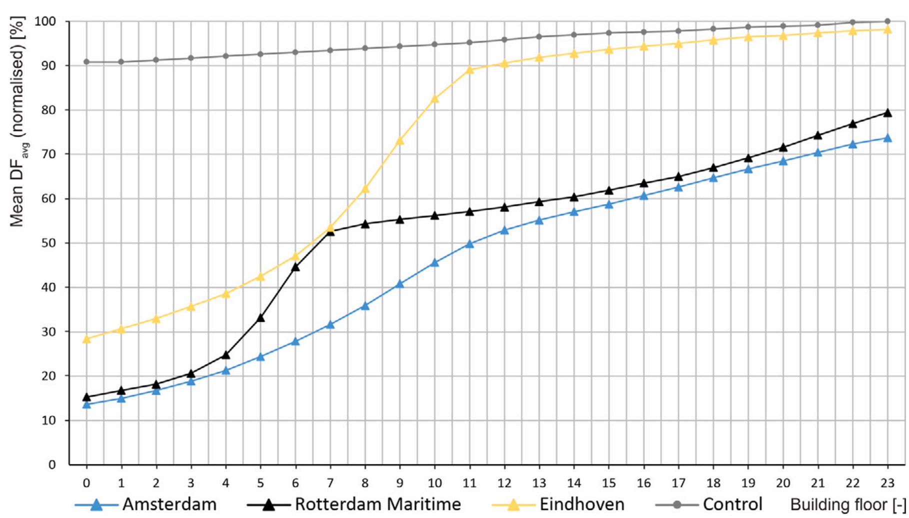

Fig. 12. Static performance of the tower apartments, shown per floor and per city. Results are normalised against the performance of an unobstructed building of the same type and averaged over different orientations.

The situation is similar but with more pronounced extremes when looking at melanopic isotropy (MI), i.e., the melanopic performance for all viewing directions across the space. Fig. 14 shows how MI is consistent with the apartment orientation when the median DA300 target is met (left column), with East facing apartments receiving more light in the morning and West facing ones in the afternoon. When only the median DA144 is met, the MI performance decreases drastically, with all orientations struggling to reach the melanopic targets for more than 50% of the view directions in the mornings of most of the year, except than in full summer. For the South orientation there are some higher peaks achieved when sunlight can pass in between urban obstructions but only in short moments of the day. These results indicate that in most of the apartments – if designed to just meet DA144 requirements – it would be very difficult to achieve a sufficient circadian entrainment in the morning hours, when it is most needed.

3.3. Performance decrease per urban density indicators

For planning purposes, it would be important to have a set of urban density indicators that can be quickly related to the expected indoor daylight performance, and facilitate a decision making process on urban planning and building design parameters that could guarantee sufficient daylight levels to all apartment units in new buildings. All photopic results from the previous analyses were aggregated per city and correlated to three urban density indicators: FSI, GSI and OSR.

As a first step, two null-hypotheses were tested: (1) the normalised photopic performance (expressed as DF and DA) is similar across different urban density indicators; and (2) the distribution of the normalised photopic performance is similar across different urban density indicators. The results of the two non-parametric statistical tests (independent-samples median test and Kruskal–Wallis H test) showed that both null hypotheses can be rejected, for either floors below and above the 10th floor (analysed separately to distinguish between floors surrounded by buildings and floors above the denser city fabric). All tests resulted in a statistical significance of 0.01 and a confidence level

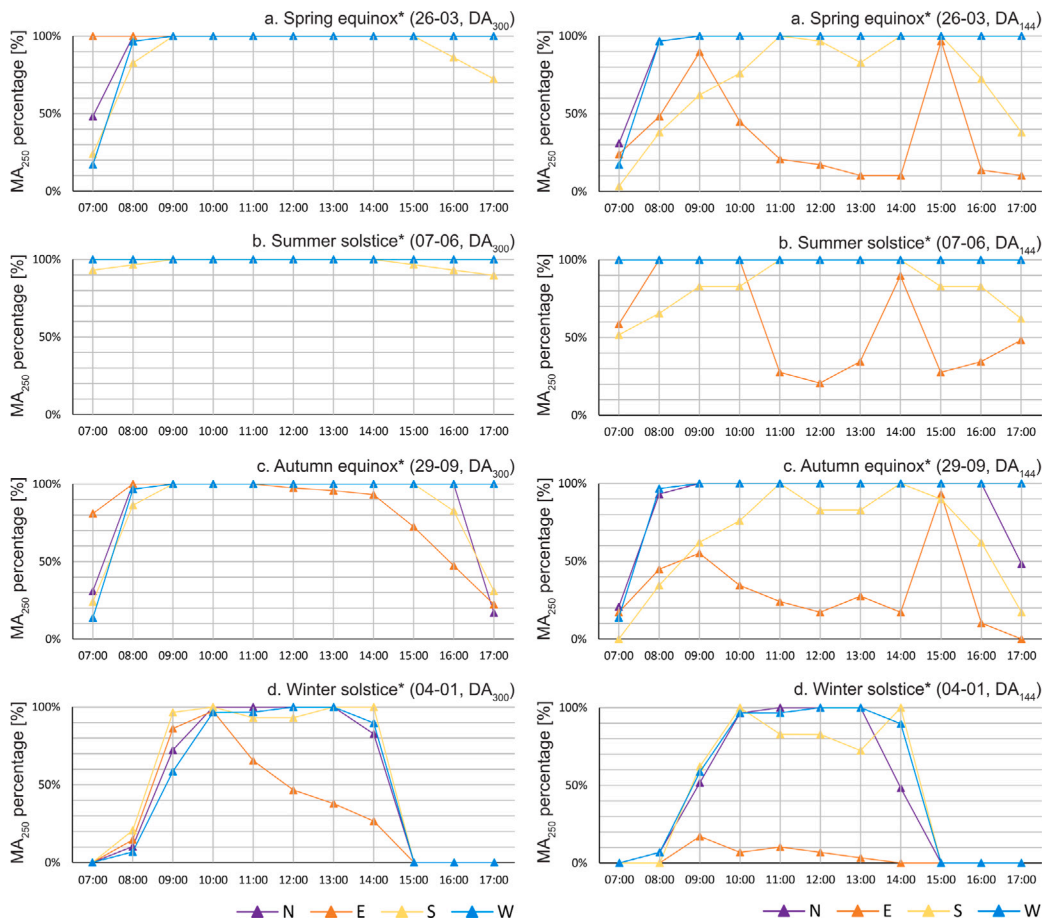

Fig. 13. The Melanopic Autonomy (MA) of a type B apartment that fulfils DA300=50% (left column) and that fulfils DA144=50% (right column). The dates were selected to be sunny days that are the closest to equinoxes and solstices. Times are in UTC+1 (no summertime). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of 99%. Hence, the six samples considered here (and each of their urban density indicator) have significantly different median values and statistical distributions when looking at the daylight photopic performance of all building units tested in their urban contexts. This means that the selected cities represent a variety of urban densities and that their urban density indicators can be further investigated as a proxy for variations in daylight performance.

To characterise the precise relationship between such indicators and the expected performance, a regression analysis is needed. The results are shown in Fig. 15. There is a weak inverse correlation between the FSI and OSR indices and daylight performance, while no correlation could be found for the GSI index. The residuals are however too large to indicate a strong relationship, mainly due to the small sample size. Future work should repeat this analysis on a larger sample, including more cities or neighbourhoods of varying density, to derive more reliable correlations.

4. Discussion

The initial analysis on unobstructed apartments confirmed previous findings (Bournas, 2020; De Luca & Sepúlveda, 2021; Hraška & Čurpek, 2024; Ticleanu et al., 2023) related to the daylight performance targets suggested in the EN 17037 standard: (1) sidelit apartments need quite high (>60%) WWR or relatively shallow floorplans (<5 m) to comply with DF target values; and (2) using Method 2 (climate-based daylight modelling) makes it easier to reach compliance than using Method 1 (daylight factor). Independently of the chosen simulation method, considering the urban context in the evaluation leads to a decrease in indoor performance (expressed as average DF and TAI) of up to 85%, especially for ground floor apartments in highly urban cities. This also indicates that – if all apartment units are designed equally to meet minimum daylight standards in unobstructed conditions – there is a very large inequality in indoor daylight quality provision between occupants of top floors and occupants of lower floors of the same building. Such inequality affects both visual (photopic) and non-visual (melanopic) indoor performance, with potential consequences for the correct circadian entrainment and general wellbeing of people living in apartments at the lower floors. Two new indicators (Melanopic Autonomy and Melanopic Isotropy, see Section 3.2) were introduced in this study to add the spatial dimension to existing melanopic performance metrics; these new indicators were found to be effective at expressing the apartments' performance without specifying fixed occupant positions, and allowed an easier comparison between apartments with different size, orientation and transparent facades. The final results of such comparison showed how recommended daylight levels for circadian health can be reached if designing for illuminance targets of 300 lx (minimum performance suggested in EN 17037) but they are much harder to achieve if designing for illuminance targets of 144 lx (equivalent to the proposed minimum performance of DF=1% in the Dutch building regulations). Even though this latter target was proposed because of its similarity with current building requirements – which underpin current building designs – the new discoveries on the importance of daylight for human health and circadian rhythms should push for more ambitious standards and higher minimum targets (Lucas et al., 2014). Furthermore, this last evaluation was performed assuming sunny sky conditions, i.e. the best possible scenario for indoor daylight availability; in reality, daylight levels are often lower, making it even

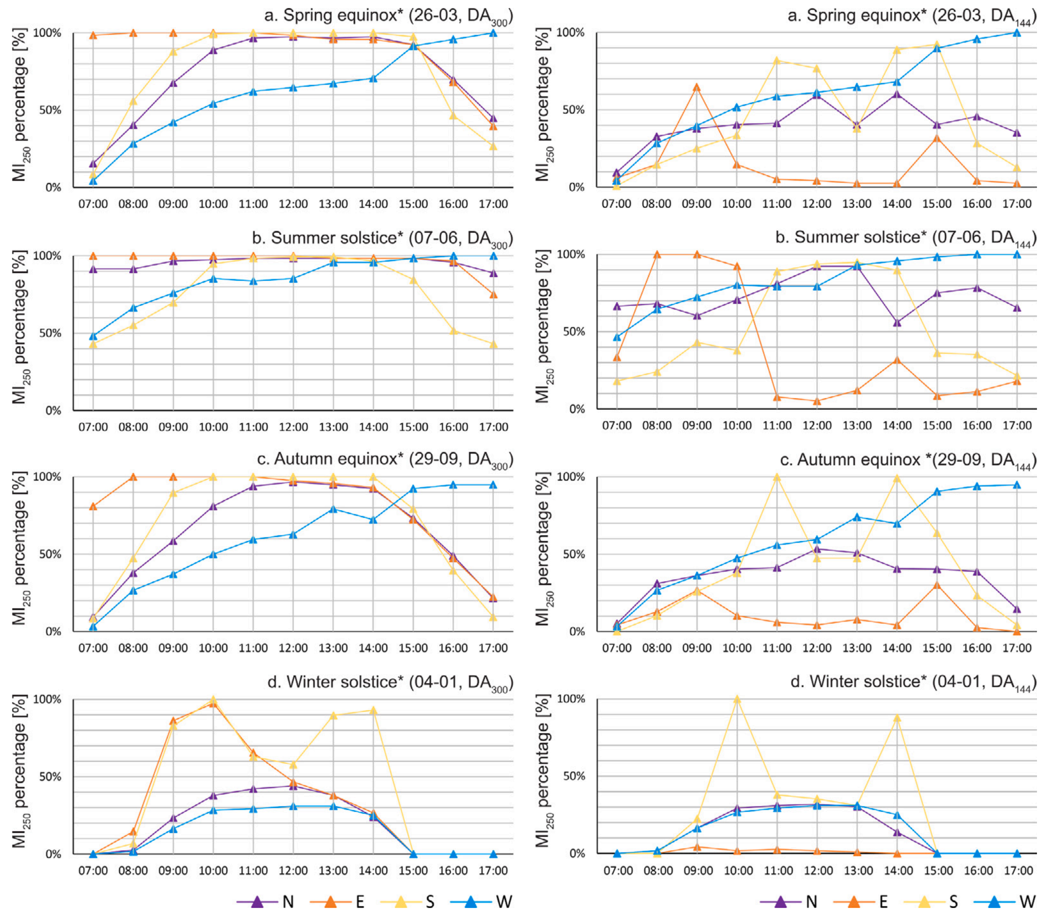

Fig. 14. The Melanopic Isotropy (MI) of a type B apartment that fulfils DA300=50% (left column) and that fulfils DA144=50% (right column). The dates were selected to be sunny days that are the closest to equinoxes and solstices. Times are in UTC+1 (no summertime). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

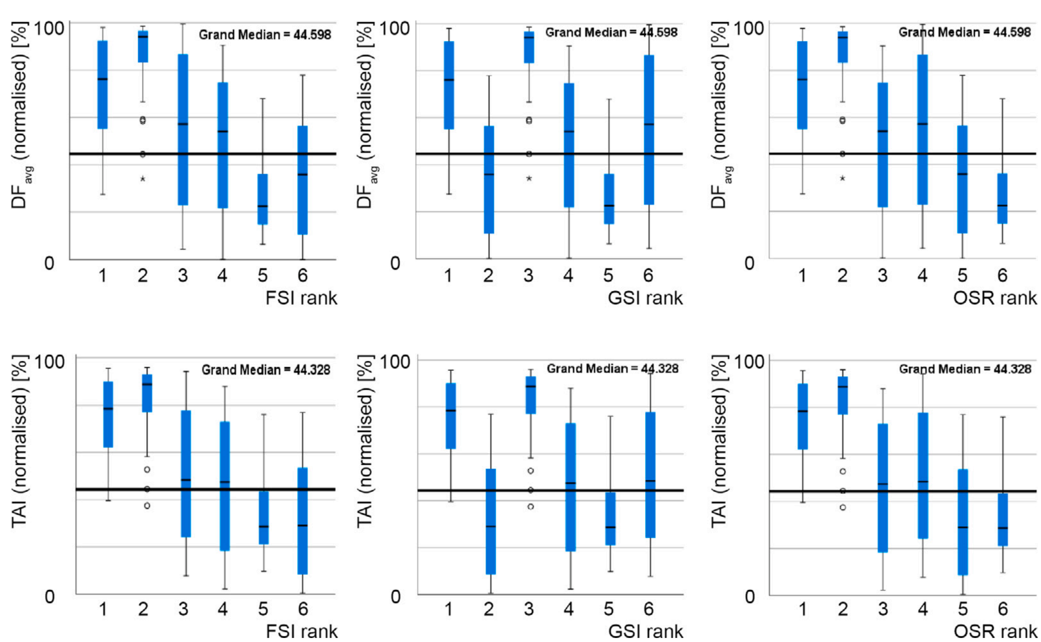

Fig. 15. Linear regression investigated for three different urban indicators (FSI, GSI and OSR) against the median and overall distribution of photopic daylight performance, both static (DF, top row) and climate-based (TAI, bottom row) metrics.

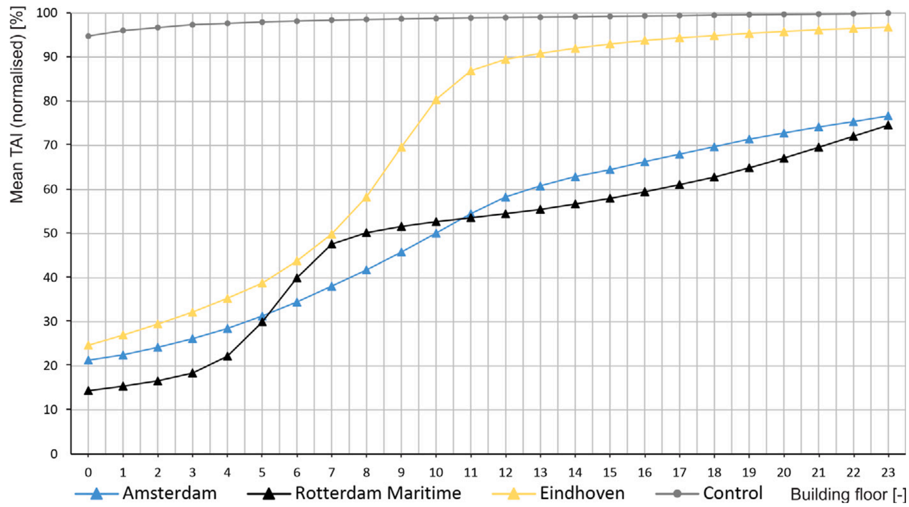

Fig. A.16. Climate-based performance of the tower apartments, shown per floor and per city. Results are normalised against the performance of an unobstructed building of the same type and averaged over different orientations.

more difficult to rely on indoor daylight to achieve melanopic targets in dense urban environments.

All apartments were assumed to have tripled glazed windows with a visual transmittance of 42.8%, in line with the requirements for high energy efficient buildings. This choice has a significant impact on the indoor daylight results, which could be higher if assuming, e.g., double glazed windows with a higher transmittance. However, the analysis concerns new buildings and future urban planning, hence it emphasises that design should be the result of an integrated evaluation that does not sacrifice energy efficiency for higher daylight performance or vice versa.

The six case study areas chosen for the study were deemed to be a good representation of different urban densities, differing from each other and leading to different daylight performances. At a qualitative level, it is possible to notice differences in aggregated indoor performance between apartments in highly urban contexts and those in urban or suburban contexts. A weak inverse correlation was also found between indoor daylight performance (both static and climate-based) and the FSI and OSR urban indicators. However, the number of case studies considered in this study does not allow for a conclusive statistical analysis on the district morphology that favours higher daylight availability. The methodology presented here should be repeated on a larger sample of areas with varying urban density.

It is important to stress that this work is solely based on simulation results and, as such, inevitably affected by simulation assumptions and errors if compared to real life measurements. Despite this, the relevance of this study is in the comparison between two different simulation approaches (with and without modelling the urban context) that can be equally adopted by architectural and engineering offices during the design stage, given the absence of clear guidelines on how to model exterior environments. The assumption is that such practitioners would use simulation to drive their decision making in terms of building and urban planning design. Thus, it is important to emphasise how decisions taken at initial design stages could have a large impact on the final daylight performance of residential apartments.

There are several implications for daylighting and building policies resulting from this work's findings. The most important of all is that building norms should provide clearer indications of how to include urban environments in simulation and modelling done during the design phase. By not doing so, the estimates obtained for any design will be an overestimation of the real situation. In lack of such clearer norms, clients, local institutions and practitioners should be made aware of the difference between simulated and actual performance if the urban environment is not taken into account in the performance evaluation process. Ultimately, including urban context in the evaluation should be a key requirement for performance-based daylight designs (e.g., parametric and generative workflows), which should reflect context- and orientation-specific attributes in the final design of windows and shading devices.

5. Conclusion

The present study evaluated the effect of urban density on simulated indoor daylight performance of typical residential apartments for the Dutch context. A low- or high-rise block was placed in six different urban environments and the visual and non-visual indoor daylight performance was assessed per floor and per apartment type. Results showed how neglecting surrounding buildings when assessing compliance with European and national standards leads to a significant overestimation – up to 85% – of daylight availability. Thus, the surrounding environments and obstructions should always be taken into account during the design process. The results of this study did not lead to a conclusive relation between urban density indicators and indoor performance, hence it is not yet possible to apply numerical factors to estimate the reduction in indoor daylight performance. It is instead essential to model the urban context surrounding a building to estimate the actual daylight performance of new designs.

Results also highlighted the large inequality in indoor daylight performance for apartments situated at the lower floors and those situated at the higher floors, with differences of around 25% for lower urban density contexts and of around 70%–80% for higher urban density contexts. Furthermore, the health benefits of daylight – assessed using melanopic performance targets – are not guaranteed if designing to just meet low visual targets (e.g., the DF=1% proposed in the Dutch building regulations). These findings emphasise the need to take urban context into account when assessing indoor daylight performance and challenge the common practice of making the same design choices (internal layout, WWR, glazing type) for all floors and orientations.

CRediT authorship contribution statement

Daniël Koster: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis. **Azarakhsh Rafiee:** Writing – review & editing, Supervision, Methodology. **Eleonora Brembilla:** Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Eleonora Brembilla reports participation in the NEN committee 'Daglichtopeningen' as a representative of the Dutch Daylight Association.

Appendix. Additional results

See (Fig. A.16).

Data availability

All 3D models, scripts and resulting data used in this work and in D. Koster's MSc thesis can be found at the link https://doi.org/10.4121/41537cd6-58ef-4f60-b001-46cf1cf4814e.

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