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Research paper

Exploitation of indoor illumination for typical flat dwellings in the Mediterranean area

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ABSTRACT

The 2018/844 Energy Performance of Buildings Directive (EU) has widened the scope of appropriate design of buildings from a pure energy performance and carbon emissions perspective to a wider scope that includes indoor comfort, and indoor air quality among others. To this effect, external parameters, especially solar energy, have a strong impact on the energy performance of buildings in Mediterranean regions, which requires careful consideration when it comes to benefiting from natural lighting while avoiding solar overheating. This paper addresses the considerations of natural lighting in the deep renovation of a housing block in the Mediterranean climate of the Republic of Malta, comparing some of the usual illuminance ranges to achieve optimal conditions based on international recommendations. DesignBuilder v7.0.0.102 has been the selected software to model the building that has been calibrated through experimental measurements. The model enabled the natural lighting conditions in the building evaluated and the effectiveness of suggested improvements to be determined. Results pointed out that the building under study satisfies the international standards about the prevention of visual discomfort only. Increasing the size of windows in identified zones, especially the first floor, was found to help improve other natural lighting characteristics. One of the proposed designs (Model 6) that replaces single-glazed with double-glazed windows that include an external spectrally-selective coating would significantly improve access to natural light bringing the building closer to the recommended levels of Annual Sunlight Exposure and reducing artificial lighting usage by up to five times. The relocation of room spaces could also reduce the use of artificial lighting.

1. Introduction

Energy efficient use in buildings is one of the most important instruments of the European Green Deal. The EU is accelerating its efforts to achieve a carbon-neutral economy by 2050 (European Commission, 2019). Energy consumption in buildings, namely dwellings, commercial entities, and public authority buildings, represents 40% of total energy consumption, mainly for heating and cooling, lighting, water heating, and ventilation. So far, only 25% of the European building stock is energy efficient (European Commission, 2020). The Renovation Wave for Europe (Directive(EU), 2018), highlights the vital importance of energy renovation of the building stock to meet Climate Target Plan 2030 to cut net greenhouse gas emissions in the EU by at least 55% by 2030, compared to 1990 levels. Furthermore, an additional 160,000 green jobs could be created in the EU construction sector through the Renovation Wave (European Comission, 2020). The main challenge for implementing energy efficiency measures lies in deep renovation projects, which may pose specific difficulties such as space limitation, technical incompatibility with new products or applications, and overall high retrofitting costs.

Despite such challenges, energy retrofitting also has the potential to provide non-energy benefits such as improved well-being and health to the occupants, as highlighted in the Energy Performance for Buildings Directive (EPBD) (Directive(EU), 2018; European Commission, 2021). One of the prominent areas to consider for occupant health is daylighting, which is constantly present in human life, directly affecting working moods, comfort, and health by circadian rhythms regulation (Sulli et al., 2019; Webb, 2006). Lack of daylighting could lead to long-term diseases risks such as diabetes (Sulli et al., 2019), cardiovascular diseases (Chellappa et al., 2020) and cancer (Acosta et al., 2017).

Despite the potential benefits of daylighting in buildings, its implementation does not automatically contribute to energy savings and improved visual comfort. To achieve these benefits,

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one needs to integrate daylighting into building design by minimising glare and solar heat gains during summer, while providing a luminous ambiance that balances direct and diffuse light. This is further elaborated in Annex N.3 in CEN/TR 15193–2 (CEN/TR15193-2:2017, 2017), which details the primary considerations to be taken for daylighting design in domestic buildings. In addition Annex F of the same standard describes a simplified approach to consider the influence of daylight on the energy needs for lighting. Furthermore, the required illumination level is often achievable by combining both natural and artificial lighting during the day (EN 16798-1:2019, 2019). This required level of illumination needs to ensure that the visual comfort for occupants is met by considering the type and duration of the occupants' activities. EN 12464-1 (EN 12464-1:2011, 2011) lists these requirements for indoor areas by task and daily activity. Moreover, the peer-reviewed literature has established specific indicators for lighting and daylighting performance (Remizov et al., 2021), while EN 15193-1 (EN 15193-1:2017, 2017) provides methods to evaluate the energy performance of lighting systems.

To enable the proper implementation of the Energy Performance for Buildings Directive (EPBD) (Directive(EU), 2018) and to support the EU Green Deal (European Commission, 2019), the EU has published a new set of Energy Performance for Building Standards (EPB) standards (EPB Center, 2022). The EPB standards include rating systems with multiple indicators (ISO 52003-1:2017(E), 2017). Member states have an obligation to describe the National Calculation Methodology (NCM) following the national annexes of the overarching standards within the EPB framework. Therefore, these standards aim to provide a more harmonised and comprehensive approach to the energy performance calculation methodology of buildings throughout the EU. More specifically, Energy Performance Certificates (EPCs), which use the NCM to calculate the energy performance of buildings, are vital to ensuring long-term renovation goals highlighted in the 2021 EPBD that require the renovation of the worst performing buildings having EPC's class F or G.

With specific reference to Malta, the Energy Performance Rating of Dwellings in Malta (EPRDM) is the NCM for dwellings. EPCs have been issued for new buildings and buildings undergoing renovation, sale or rent since 2009 (Degiorgio and Barbara, 2016). For non-dwellings, the Simplified Building Energy Model for Malta (iSBEM-mt) is employed as the NCM. Both software use the monthly quasi steady-state approach in accordance with EN ISO 13790 (ISO 13790:2008(E), 2008) for deriving energy performance calculations as opposed to the updated hourly approach described in the new EPB standards. Due to this reason, and the lack of overall and partial energy performance indicators (detailed in the new EPB standards ISO 52000-1 (ISO 52000-1:2017(E), 2017), and ISO 52018-1 (European Commission, 2011), the NCM for Malta does not sufficiently consider the impact of natural daylighting vis-a-vis energy savings (ConsultationDocument, 2021), health, well-being and visual comfort of occupants, although these criteria are being given priority in the new EPBD.

Furthermore, despite the high potential to incorporate daylighting design into buildings in Malta, given that Malta benefits from 3000 h of sunshine per year, few peer-reviewed local studies have attempted to study ways to optimise its implementation. Gatt (2015) used EnergyPlus (EnergyPlus, 2021) in DesignBuilder to quantify the financial feasibility and potential energy savings both when incorporating on/off control of artificial lighting (T5) via lux sensors and dimming for different oriented classrooms in Malta. It was found that incorporating lux sensors to control lighting on/off is financially feasible based on a net present value (NPV) analysis. However, to the authors' best knowledge, a specific study incorporating on-site measurements and Radiance to quantify the potential of daylighting and visual comfort for typical flatted apartments in Malta has not yet been carried out.

Therefore, this research studies in detail the daylighting potential and visual comfort of a typical flatted dwelling in Malta using different quantifiable metrics as indicators of daylighting performance in the building. Such indicators may also be considered for implementation in future enhancements to the National Calculation Methodology (NCM). DesignBuilder, calibrated through experimental measurements, was the selected software to model the building and generate these indicators. Based on the results of these indicators, the study has highlighted that the original design fails to offer good natural lighting levels for several human activities. Therefore, proposals to improve the daylighting potential of the typical building under study are made, considering how different proposals also affect the overall energy performance of the building. Suggested improvements include changes in the use of some of the rooms and the modification of the size and material used in the windows to increase visual comfort and reduce the need for artificial lighting. Such results contribute to a wider scope of sharing knowledge and solutions for similar buildings that are typically found in many Euro-Mediterranean and northern African countries.

This research first gives a brief review of the metrics used to evaluate daylight performance in buildings in the literature, followed by a description of the proposed methodology to assess the daylight performance of a building. After, the research applies the methodology that uses multiple state -of-the-art software to a typical flatted building case study in Malta. Several measures to enhance the daylight potential of the building under study are then proposed and evaluated.

2. Metrics to evaluate daylight performance in buildings

Indoor natural lighting is highly dependent on the design of the building, as well as the surrounding conditions. Therefore, evaluating visual comfort and energy efficiency due to natural lighting requires an accurate estimate of the amount of natural light at any point in the internal space. Traditionally, the parameter that determines the relationship between the interior and exterior lighting of a building is the Daylight Factor (DF) defined as (Aishaibani, 1996):

$$\mathrm{DF} = \frac{\mathrm{L_{in}}}{\mathrm{L_{out}}}, \tag{1}$$

where $\mathrm{L_{in}}$ is the illuminance measured at a point inside the workspace, and $\mathrm{L_{out}}$ is determined outside. This factor, determined under cloudy sky conditions (CIE, 1955; Moon and Spencer, 1942) allows a stable characterisation of the luminous environment by eliminating the dependence on the temporal variable and the orientation of the building space under study.

Other studies have developed a dynamic metric compared to the traditional static analysis that represents the DF. Such dynamic metrics consider the variability of natural lighting from the conversion of the solar radiation data contained in the climate files commonly used in building energy simulation programs under sky conditions standardised by the CIE using Pérez's sky model (Acosta et al., 2015). From this conversion, Useful Daylight Illuminance (UDI), UDI autonomous (UDI-A) (Mardaljevic et al., 2012), Annual Sunlight Exposure (ASE) (Basurto et al., 2016) and Daylight Autonomy (sDA), are determined for one year. Hraška (2018) highlighted the negative aspects of dynamic metrics due to their complexity of use, high calculation time and complex experimental verification. In contrast, Carlucci et al. (2015) pointed out the advantages of their application since these metrics preserve the vital information of the illuminance time series. Table 1 describes the most common dynamic metrics used are described in the literature.

Table 1
Dynamic metrics for annual daylighting evaluation during occupied hours (08:00–18:00).

Metric	Temporal analysis in the space	Analysis by space	Target
Useful Daylight Illuminance (UDI) $UDI_{100-500\ lx}$	Annual Occurrence of daylight illuminances falls in the range 100–500 lux (Mardaljevic et al., 2012).	Percentage of floor area that falls in the range 100–500 Lux more than 50% of the time (DesignBuilder, 2021). **International recommendation:** –	Evaluating the effectiveness of natural light that enters the building, either independently or in conjunction with artificial lighting.
UDI autonomous (UDI-A) $UDI_{300-3000\ lx}$	Annual Occurrence of daylight illuminances falls in the range 300–3000 lux (Mardaljevic et al., 2012).	Percentage of floor area that falls in the range 300–3000 Lux more than 50% of the time (DesignBuilder, 2021). **International recommendation:** –	Analysing the possibility of avoiding the use of artificial lighting.
Annual Sunlight Exposure (ASE) $ASE_{1000\ lx,250\ h}$	It is the number of hours per year a point on the working plane receives direct sunlight greater than a threshold value (1000 lux) (DesignBuilder, 2021).	Percentage of the area in the space where the direct sunlight illuminance is greater than 1000 lux for more than 250 h of the occupied hours (08:00–18:00) in a year (AL-Dossary and Kim, 2020). **International recommendation:** Preferred: $ASE_{1000\ <\ lx,250\ h} < 3\%$ Neutrality: $ASE_{1000\ <\ lx,250\ h} < 7\%$ Accepted: $ASE_{1000\ <\ lx,250\ h} < 10\%$	Analysing the intensity of lighting levels causing discomfort on humans.
Spatial Daylight Autonomy (sDA) $sDA_{300\ lx,50\%}$	It is expressed as the percentage of occupied time during the year when a minimum work plane illuminance threshold of 300 lux can be maintained by daylight alone (DesignBuilder, 2021).	Percentage of floor area that exceeds a 300 lux illuminance level more than 50% of the occupied hours (08:00–18:00) in a year (AL-Dossary and Kim, 2020). **International recommendation:** Preferred: $sDA_{300\ lx,50\%} > 75\%$ Nominally accepted: $sDA_{300\ lx,50\%} \in 55-74\%$	Summarising the frequency in which an illuminance threshold can be maintained by natural light on its own.

2.1. International recommendations for daylight design

The daylight illuminance pattern widely varies across the work plane, from the front area, near the fenestration, to the backside of the room. Generally, the acceptance of uniform outdoor illuminance of the standard overcast sky is commonly implemented (Littlefair, 2011). However, it does not consider the contribution of direct sunlight, which also leads to differences between several locations of the sky dome (Yun and Kim, 2018). These potential differences in the available luminance affect the indoor light distribution (Alshaibani, 2016). Accordingly, the methodology followed to predict the illuminance is more realistic if it can accommodate in some way the influence of numerous sky typologies (Nabil and Mardaljevic, 2005).

UDI ranges and criteria vary with the application, target, and author (Basurto et al., 2016; Brembilla and Mardaljevic, 2019). For writing and reading in interior rooms, the UK Chartered Institution of Building Services Engineers (CIBSE) recommends an illuminance level of 500 lx (Raynham, 2012). When electrical lighting is used to meet these illuminance levels, the design often aims to deliver this level evenly on the working plane (Nabil and Mardaljevic, 2006). However, in terms of UDI distribution ($UDI_{100-500\,lx}$), there is no specified target for lighting uniformity (Costanzo et al., 2018). The ($UDI_{100-500\,lx}$) range summarises the annual occurrence of illuminances that falls in a range considered 'useful' by occupants (Marins et al., 2019), which falls in the 100 to 500 lux range. Therefore, this value should be as large as possible (Mardaljevic et al., 2009). UDI-autonomous ($UDI_{300-3000\,lx}$) focuses on the range of 300 to 3000 lux since it is the least likely to require artificial lighting (Mardaljevic et al., 2012).

The Spatial Daylight Autonomy ($sDA_{300\,lx,\ 50\%}$) is recommended by the Illuminating Engineering Society of North America (IESNA) (Andersen et al., 2012). It informs on the percentage of space reaching a threshold illuminance value for 50% of a specified amount of time over a year. This target illuminance is commonly set to 300 lux. sDA metric falls in the interval of 0% to 100% of the floor area. A floor area of 75% or larger is considered optimal, but a range between 55%–74% is nominally accepted (AL-Dossary and Kim, 2020).

Natural daylight has good potential benefits, but if not properly controlled may also produce glare that leads to visual discomfort and overheating (Ticleanu et al., 2013) Glare results when illuminance values exceed 1000 lux for more than 250 h of the occupied hours (08:00-18:00) in a year ($ASE_{1000\,lx,25\,h}$) in a determined percentage or for the total area (AL-Dossary and Kim, 2020). The proposed values for $ASE_{1000\,lx,250\,h}$ in the spatial analysis falls into three ranges[1] : Preferred range ($ASE_{1000\,lx,250\,h} < 3\%$); Neutrality ($ASE_{1000\,lx,250\,h} < 7\%$), and Accepted ($ASE_{1000\,lx,250\,h} < 10\%$).

2.2. European recommendations for the energy performance of buildings

The standard EN 15193-1 (EN 15193-1:2017, 2017) links the Energy Performance of a Building (EPB) (ISO 52000-1:2017(E), 2017) with the Lighting Energy Numeric Indicator (LENI) of a space to a particular task. LENI aims to meet the lighting requirements efficiently, according to the usage of each area in which the task will take place. Mainly, the lighting system of each area designs its lighting power to provide the illuminance level that the task activity sets. Hence, it is known as the maintained illuminance. Daylight contributes entirely or partially to it, while automatic or manual switching of artificial lighting ensures the appropriate balance of natural to artificial light. The indoor illuminance distribution by sunlight links all these concepts through analytical expressions (CEN/TR15193-2:2017, 2017).

The maintained illuminance is available in EN 12464-1 standard in Europe (EN 12464-1:2011, 2011), IESNA in the United States (IESNA, 2003), and CIBSE in the United Kingdom (Raynham, 2012). The illuminance levels recommended by each standard differ slightly. This research pursues the requisites of EN 12464-1 (EN 12464-1:2011, 2011) under the set of European standards of ISO 52000-1:2017(E) (2017), shown in Table 2.

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[1] ASE is the percentage of the area in the space where the direct sunlight illuminance is greater than a specified level. ($ASE_{1000\,lx,250\,h}$): percentage of the area where illuminance values exceed 1000 lux for more than 250 h of the occupied hours (08:00-18:00) in a year.

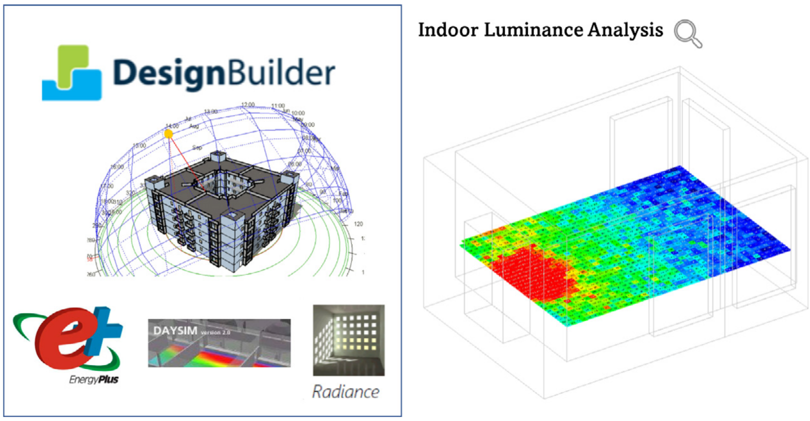

Fig. 1. DesignBuilder uses EnergyPlus, Daysim, and Radiance to generate performance data.

Table 2
Lighting requirements for indoor areas, tasks, and activities for EN 12464-1 (EN 12464-1:2011, 2011).

Location	Task	Recommended illumination level
Traffic zones	Circulation areas and corridors	100 lux
	Stairs, escalators, travolators	150 lux
Rooms for general use	Corridors: during the day	200 lux
	Day rooms	200 lux
Rest, sanitation, and first aid rooms	Cloakrooms, washrooms, bathrooms, toilets	200 lux
Offices	Writing, typing, reading, data processing	500 lux
Restaurants and hotels	Kitchen	500 lux

2.3. Description of the software and link to international recommendations

Computational power improvements have allowed the solar architectural design to be optimised, particularly in the field of lighting simulation (Rucińska and Trzaski, 2020), leading to the predominance of numerical simulation and physically-based ray-tracing over analytical or empirical solutions (Acosta et al., 2015). Radiance (DesktopRadiance, 2021) is the most widely used validated simulation tool. It incorporates a state of-the-art and practical ray-tracing approach to achieve sufficient accuracy in a reasonable simulation time.

Radiance software has been incorporated in software packages such as OpenStudio (OpenStudio, 2021), HoneyBee (HoneyBee, 2021), DIVA (Solemma, 2021) or DesignBuilder (DesignBuilder, 2021), to offer a holistic approach towards the study of sustainable applications in buildings (Labayrade and Launay, 2011). Specifically, the annual daylight modelling option of DesignBuilder runs through the Daysim simulation engine (DAYSIM, 2021), a validated software based on the Radiance simulation engine for daylight analysis and calculation of annual daylight availability in buildings (DesignBuilder, 2021). In addition, it uses the lightswitch occupant behaviour model to mimic occupant use of personal controls such as light switches and Venetian blinds and to predict energy savings from automated lighting controls such as occupancy sensors and photocell-controlled dimming systems (Reinhart, 2004).

3. Methodology

The commercial software package Design Builder v.7.0.0.102 (DesignBuilder, 2021) has been used in this study. This software implements EnergyPlus (EnergyPlus, 2021), Daysim (DAYSIM, 2021), and Radiance (Radiance, 2021) package interfaces to generate natural lighting performance data and dynamic daylight metrics for buildings (DesignBuilder, 2021) (Fig. 1).

The proposed methodology depicted in Fig. 2 uses the Radiance model linked to DesignBuilder to enable a seamless interface with the other two engines of DesignBuilder, namely EnergyPlus and Daysim. This interface gives the advantage of assessing the impact of daylighting using a modular but simultaneously allows for a whole-building integrated approach. More specifically, the Radiance software is a backward ray-tracing engine (Radiance, 2021) that generates the irradiance and illuminance data from the EnergyPlus weather file in DesignBuilder and the Perez all-weather sky model (Liu et al., 2020). The meteorological variables for carrying out the simulations are user selectable from a weather file via the application "Weather Statistics and Conversion" included in the EnergyPlus package (EnergyPlus, 2021). In this case, the hourly mean horizontal diffuse and direct irradiation data were provided. In addition, Daysim allows the calculation of several dynamic metrics for evaluating daylight potential in complex buildings, such as Daylight Autonomy (SDA), Annual Sunlight Exposure (ASE), and Useful Daylight Illuminance (UDI), previously defined in Table 1.

A 3D Radiance model of the building is first set-up. To increase confidence in the model's results for the analysis, the model was hourly calibrated with indoor illuminance measurements collected for fourteen days in the centre of the zone under study. The most critical inputs, including reflectance and transmittance of the different surfaces were fine-tuned until the illuminance simulated output from the Radiance model was deemed hourly-calibrated with metered data according to the statistical parameters recommended by the ASHRAE Guideline (2014) (ASHRAE, 2021) as shown in Eqs. (2)–(3). To achieve hourly calibration, the resulting normalised mean bias error (NMBE) should be lower than 10% and the coefficient of variation of the root of the mean square error cv(RMSE) should be lower than 30%. These statistics are defined by Eqs. (2) and (3), respectively.

$$\mathrm{NMBE} = \frac{\sum(\mathrm{V_{exp}} - \mathrm{V_{mod}})}{(\mathrm{N}-1)\ \overline{\mathrm{V}}_{\mathrm{exp}}} \cdot 100, \tag{2}$$

$$\mathrm{cv\,(RMSE)} = \frac{\sqrt{\frac{\sum(\mathrm{V_{exp}} - \mathrm{V_{mod}})^2}{(\mathrm{N}-1)}}}{\overline{\mathrm{V}}_{\mathrm{exp}}} \cdot 100, \tag{3}$$

where $\mathrm{V_{exp}}$ are the experimental data recorded during the experimental campaign, $\mathrm{V_{mod}}$, are the modelled variable, $\overline{\mathrm{V}}_{\mathrm{exp}}$ is the average value of the experimental data, and N the number of experimental data. cv(RMSE) shows the ability of the model to

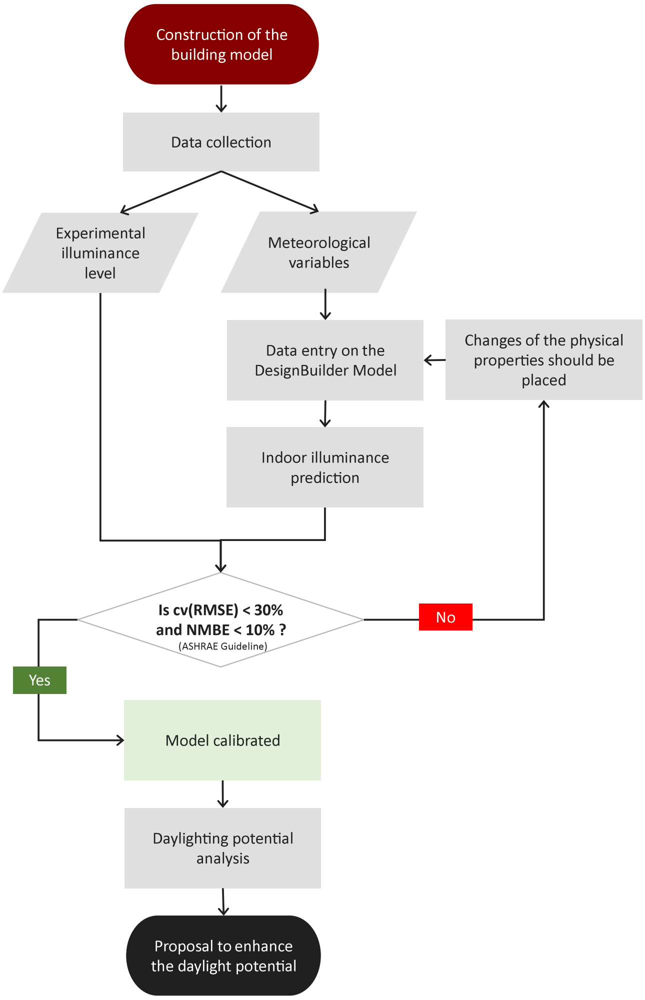

Fig. 2. Methodology flow chart.

recreate the data, and the NMBE tests the bias of the predicted output versus the reference (Ruiz and Bandera, 2017).

Once the calibrated model is available, the daylighting potential can be analysed by calculating the dynamic metrics that characterise the building under the current conditions and potential measure upgrades to improve daylighting performance.

4. Case study

A social housing block located in Żabbar, Malta (35°52′38″N; 14°32′17″E, 61 m above sea level), has been analysed using the methodology described in Section 2. The complex comprises forty apartments equally distributed on five storeys (Notation: 0 is the first-floor, 2 is the third floor, and 4 is the fifth floor) each having a total internal floor area of 109 square meters, as shown in Fig. 3. Each apartment comprises one bathroom, kitchen, living room, and three bedrooms. The block was built in the mid 1990's, using typical layouts in terms of geometry and building envelope properties in this era, such as the locally available globigerina limestone blocks.

To improve the energy performance of the social housing building stock, the Housing Authority embarked on a building renovation programme in collaboration with the Institute for Sustainable Energy of the University of Malta. During the first stage, the plan identified a social housing block to act as a pilot project for energy renovation to tackle one of the policy measures put forward in the policy action plan for Malta during the Interreg Europe ZeroCO2 project (Gatt and Yousif, 2020, 2018). The Interreg Europe ZeroCO2 project focused on promoting near-zero CO_2 emission buildings due to energy use in public buildings and social housing.

Table 3
Properties of buildings that have a significant impact on daylighting.

Glazing (1 layer, 6 mm thickness)	Total solar transmission (dim)	0.819
	Direct solar transmission (dim)	0.775
	Light Transmission(dim)	0.881
	U-Value (W K^{-1} m^{-2})	5.718
Surfaces (ceilings and floor)	Reflectance (dim)	0.5

Given Malta's small size, only one climate zone described in Gatt and Yousif (2020) is defined. Malta has a Mediterranean climate according to the Köppen climate classification (Csa), with very mild winters and hot summers (Kottek et al., 2006).

The yearly global solar irradiation on the horizontal amounts to 1825 kWh/m^2, making it one of Europe's highest solar radiation falling places (ESMAP, 2020). Typical summer temperatures may peak at 33 °C in the early afternoon and drop to a minimum of around 26 °C at nightIn winter, the maximum temperatures would be around 16 °C, dropping to an average of 10 °C at night. Malta receives no snow, and the average wind speed is about 4 m/s, mostly blowing from the North-west, with the highest wind speeds occurring in March (González and Yousif, 2015).

The weather file for the daylighting analysis used in this study was compiled by the Institute for Sustainable Energy (Malta) (Yousif, 2015) and corresponded to the year 2010, as used in the National Calculation Methodology (NCM) (iSBEM-mt) for energy performance certification of non-residential buildings. Fig. 4 shows univariate plots depicting the monthly distribution for the horizontal direct and diffuse solar irradiance for the year 2010.

To calibrate the Radiance model set up from DesignBuilder, an experimental campaign was carried out for the period between 24th September to 7th October 2021. A calibrated luxmeter, model ML-0200SO (EKO, 2020), and a dedicated data logger recorded indoor illuminance data on the second floor of the building, as shown in Fig. 5, and denoted by a red star. The sensor was placed on an auxiliary support at the centre of the room and 0.85 m above ground level. The dimension of the room's floor is 4.16 m deep, and 3 m wide. The opening is a glass door (1.9 high, 1.18 m. wide) in the centre of the wall facing the inner courtyard. Data were recorded every 30 s and averaged on an hourly basis.

The building parameters that significantly impact daylighting were manually tuned, and the hourly illuminance values of the modelled and experimental data were compared. The calibration parameters include the total solar transmission, direct solar transmission, light transmission and global thermal transmission (U-Value) of glazing, and reflectance of the ceilings and floor shown in Table 3. These parameters were manually tuned until calibration was validated using cv(RMSE) and NMBE metrics defined previously. The resulting NMBE and cv(RMSE) are 1.24% and 25.8%, respectively, when the parameter inputs depicted in Table 3 are applied. The model can therefore be considered hourly-calibrated according to ASHRAE Guideline (2014) (ASHRAE, 2021).

5. Daylighting potential analysis

Fig. 6 depicts a univariate plot for illuminance data's daily metered hourly distribution. A quality test discarded the data that corresponds to outliers (Ruzmaikin and Guillaume, 2014). The room in which the illuminance data was metered is oriented North-West, thus giving the highest illuminance values in the

Fig. 3. Housing Complex in Żabbar, Malta.
Source: Google Earth.

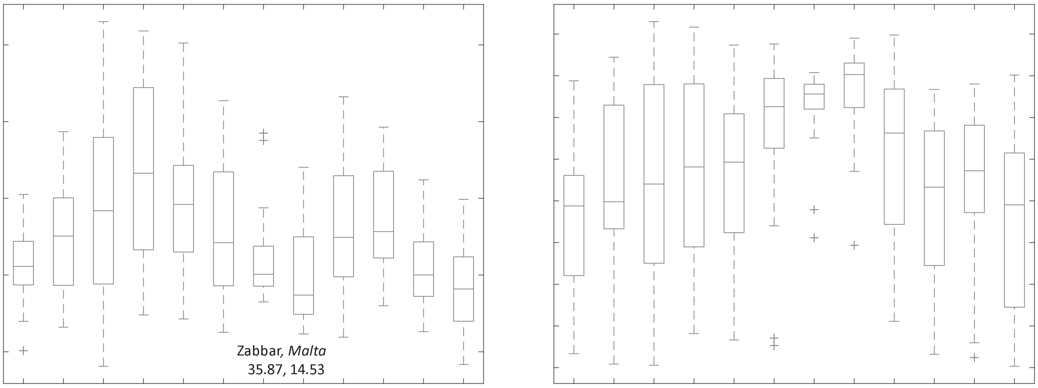

Fig. 4. Boxplot of daily horizontal diffuse and normal direct irradiance (kW/m^2) calculated from the experimental hourly mean data, recorded in Malta (weather file).

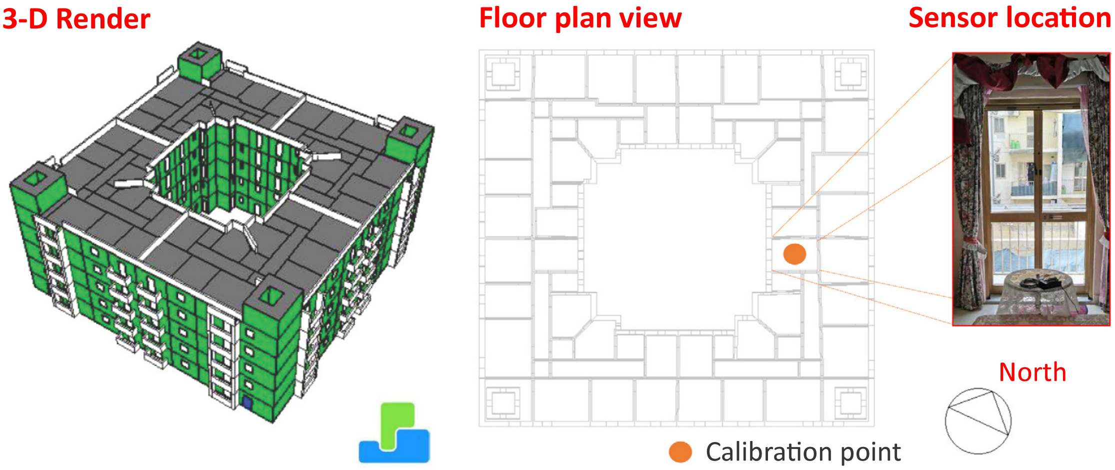

Fig. 5. 3D Sketch-Model built-in Design Builder, plan section view of the second floor (the red point depicts the illuminance measurement point) and the experimental equipment arrangement. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

afternoon when the sun is in the western sky. As can be seen, the average indoor illuminance between 08:00 and 14:00 is 180 lux. This average falls in the range of illuminance 100–500 lux, considered useful for visual comfort (EN 12464-1:2011, 2011; Nabil and Mardaljevic, 2005). However, it only meets visual comfort requirements for circulation spaces but not for more demanding tasks such as reading and writing, which require an illuminance of 500 lux. It was also noted that there are a few outliers with

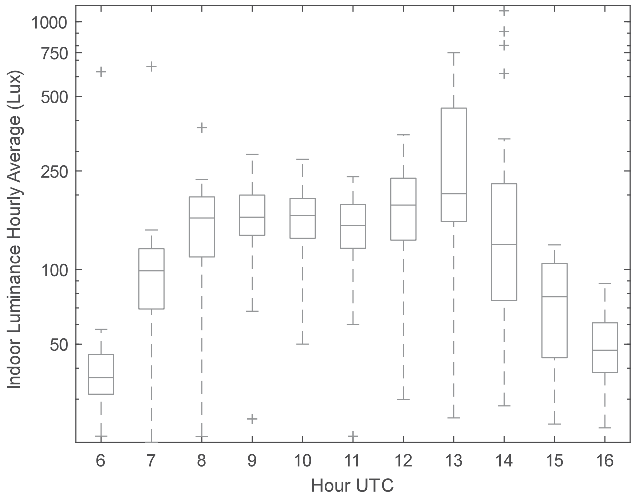

Fig. 6. Indoor illuminance hourly average (lux) for the period 24th September–7th October 2021 at the calibration point (red star in Fig. 5).

Table 4
Area and percentage for the floors (first, third and fifth) that satisfies the requirements of the UDI metric ($UDI_{100-500\ lx}$).

Floor level	First	Third	Fifth
UDI (m^2)	241.1	230.1	303.6
UDI (%)	27.6	26.4	34.8

high lux levels, but these occur during short instances, probably due to reflection from the glazed door, and therefore it is not likely that the room suffers from excessive glare.

Once the building lighting model was calibrated, the dynamic metrics defined in Table 1 were calculated using the Daysim tool implemented in DesignBuilder software for the current lighting conditions in the building. As previously explained, these hourly basis metrics allow one to establish the daylight potential of the building and the extent to which the needs of the occupants in terms of visual comfort are met.

5.1. Useful daylight illuminance ($UDI_{100-500\,lx}$)

This section performs an analysis of the building in terms of $UDI_{100-500\,lx}$. Fig. 7 shows a graphical light distribution map for the yearly average of the $UDI_{100-500\,lx}$ for the first, third and fifth floors. It is observed that all rooms on the fifth floor that have access to fenestration from either the external façade or the internal courtyard achieve a $UDI_{100-500\,lx}$ of 50% or more. In contrast, for the first floor, the rooms having fenestration on the external façade similarly achieve a $UDI_{100-500\,lx}$ of 50% or more, the rooms with fenestration exposed to the internal courtyard have a $UDI_{100-500\,lx}$ close to 0% for 90% or more of their floor area. This implies that the current fenestration openings on the first floor are not sufficient to take advantage of the daylight from the internal courtyard.

Table 4 tabulates the current values of $UDI_{100-500\,lx}$ for the floors shown in Fig. 7. It includes the area and percentage for each floor that satisfies the requirements of the $UDI_{100-500\,lx}$ for more than 50% of the occupied hours (08:00-18:00) in a year.

The highest UDI is achieved on the fifth floor (34.8%), while the third and first floors achieve a lower UDI value of 27.6% and 26.4%, respectively. For all these floor cases, the maximum potential $UDI_{100-500\,lx}$ always falls below 35%, meaning that only a small area of the building meets the recommended criteria.

Table 5
Area and percentage for the first, third, and top floors, respectively, that satisfies the requirements of the UDI-A metric ($UDI_{300-3000\ lx}$).

Floor level	First	Third	Fifth
UDI-A (m^2)	66.2	68.5	97.2
UDI-A (%)	7.6	7.9	11.1

5.2. UDI-A ($UDI_{300-3000\,lx}$)

This section performs the analysis of the building in terms of $UDI_{300-3000\,lx}$. Fig. 8 shows a comparison of the UDI-A ($UDI_{300-3000\,lx}$) on the first floor. The *x*-axis in Fig. 8 identifies the label of each room corresponding to the floor plan. The *y*-axis is the percentage of the floor area (of each room) in which the illuminance level falls in the range 300–3000 lux for more than 50% of the occupied hours (08:00-18:00) in a year. Furthermore, the label termed '*difference*' and visualised in orange in Fig. 8 shows the $UDI_{300-3000\,lx}$ difference of a room compared to the other room in the opposite orientation, for example, the $UDI_{300-3000\,lx}$ difference between room 1, found in zone 1, and room 1′,located in zone 2.

Clearly, the $UDI_{300-3000\,lx}$ value varies according to the room's location overlooking the internal yard or the façade. On the other hand, zones 3 and 4 show slightly different distribution, as the building is not exactly facing cardinal directions (approx. 26 degrees from the south). Zone 2 has, in general, less annual UDI-A frequency (rooms 1′ to 6′ in zone 2 versus 1 to 6 in zone 1), but the rooms of locations 8′ to 11′ have the best performance (versus 8 to 11 in zone 1). Therefore, North-West orientation showed worse results than South-East in terms of UDI-A

Table 5 summarises the annual frequency of UDI-A for three representative building floors. It records the percentage of the floor area and the actual area of each floor in which the illuminance level falls in the range 300–3000 lux more than 50% of the occupied hours (08:00-18:00) in a year.

Therefore, on average, less than 12% of the floor area can reach 300–3000 lux during half of working hours without artificial lighting supplement. As expected, higher UDI-A values are obtained at higher floor levels, with the UDI-A metric being 7.6% at the first floor area and reaching 11.1% on the fifth floor.

5.3. Discomfort glare ($ASE_{1000\,lx,250\,h}$)

This section analyses discomfort glare for the building by applying the $ASE_{1000\,lx,250\,h}$ metric. Fig. 9 shows a visual discomfort glare distribution light distribution map for the fifth floor. A zero ASE value means that the room is not affected by glare. The *y*-axis is the room label defined in order of ASE magnitude, with the rooms having the lowest label number having the highest ASE magnitude. The recommendation is to avoid the zone locations that exceed the recommended $ASE_{1000\,lx,250\,h}$ values.

The results clearly show a higher risk of discomfort on the western side than on the eastern side, as the building is off-centre to the southwest and is therefore exposed to higher solar radiation levels in the afternoon. A shading system, including shutters, awnings, or blinds, could help avoid these uncomfortable situations (Brembilla et al., 2019). On the fifth floor, only 15 rooms exceed the preferred $ASE_{1000\,lx,250\,h}$ level, and four rooms exceed the accepted range. According to the results of Table 6, the areas affected by glare according to the $ASE_{1000\,lx,250\,h}$. There are 13.3 m^2 on the first floor, 17.2 m^2 in the third and 23.4 m^2 on the fifth floor, equivalent to 2.7% of the fifth floor area. In addition, all floors have an average value of $ASE_{1000\,lx,250\,h}$ that falls in the Referred as defined in Table 1.

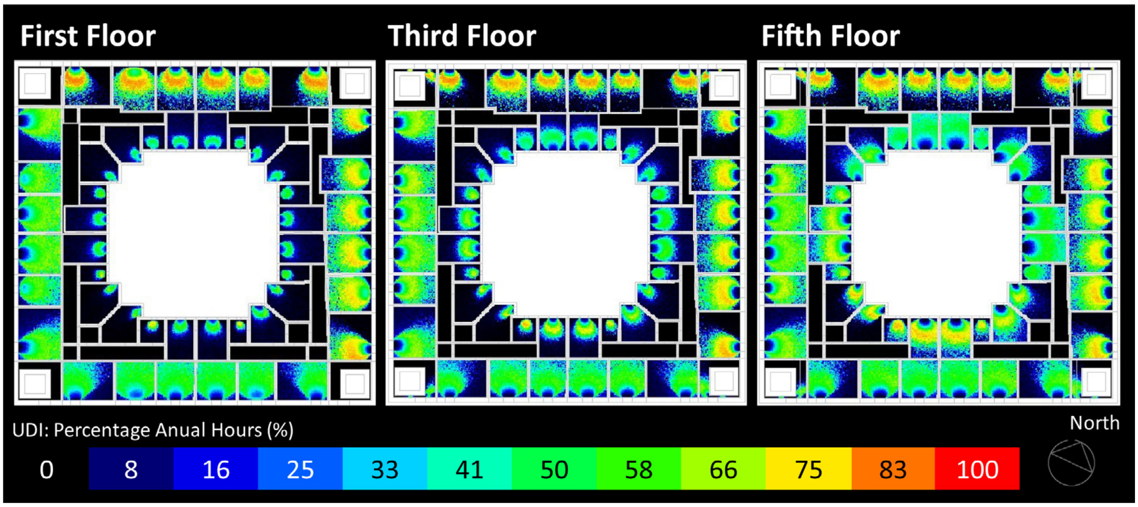

Fig. 7. $\text{UDI}_{100-500\,\text{lx}}$ distribution in the study case building.

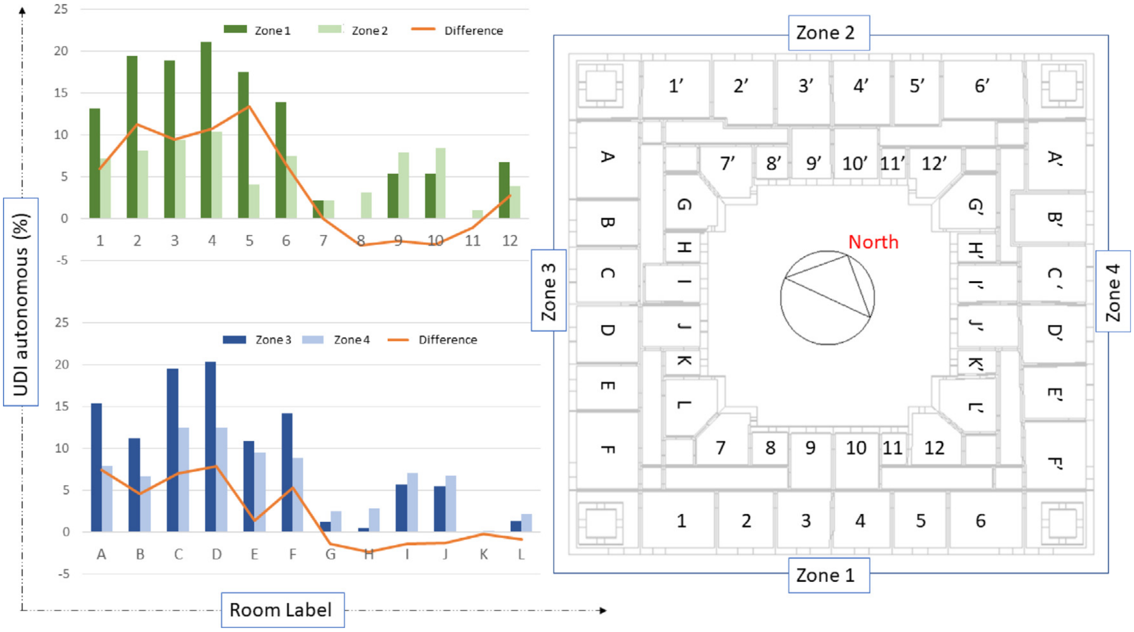

Fig. 8. $\text{UDI}_{300-3000\,\text{lx}}$ distribution in each room of the case study building. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 6
Area and percentage for the first, third and fifth floors, respectively that satisfies the requirements of the ASE metric $\text{ASE}_{1000\ \text{lx},250\ \text{h}}$.

Floor level	First	Third	Fifth
$\text{ASE}_{1000\ \text{lx},250\ \text{h}}$ (m^2)	13.3	17.2	23.4
$\text{ASE}_{1000\ \text{lx},250\ \text{h}}$ (%)	1.5	2.0	2.7

5.4. Spatial daylight autonomy ($\text{sDA}_{300\,\text{lx},50\%}$)

This section analyses spatial daylight autonomy based on the $\text{sDA}_{300\,\text{lx},50\%}$. Fig. 10 shows the distribution of the Spatial Daylight Autonomy ($\text{sDA}_{300\,\text{lx},\,50\%}$) on the first, third and fifth floors according to the % annual number of hours. It can be noted that for areas within the zones that have a numerical value for % annual number of hours falling within or larger than the pale green colour in the graphical key of Fig. 10, the conditions of $\text{sDA}_{300\,\text{lx},\,50\%}$ are reached. More specifically, only rooms 9′, 10′, I′ and J′ on the fifth floor (depicted in Fig. 10) reach $\text{sDA}_{300\,\text{lx},\,50\%}$ criteria for more than half of the room.

For the $\text{sDA}_{300\,\text{lx},\,50\%}$ metric, the Nominally Accepted range is an illuminance exceeding 300 lux, retained for about 50% of the occupied hours (8:00–16:00) in a year (Andersen et al., 2012). Table 7 shows the results of this metric for the case study.

6. Proposal of measures to enhance the daylight potential inside buildings

Based on the results from the various daylight metrics, it is clear that there is potential to improve the daylighting potential

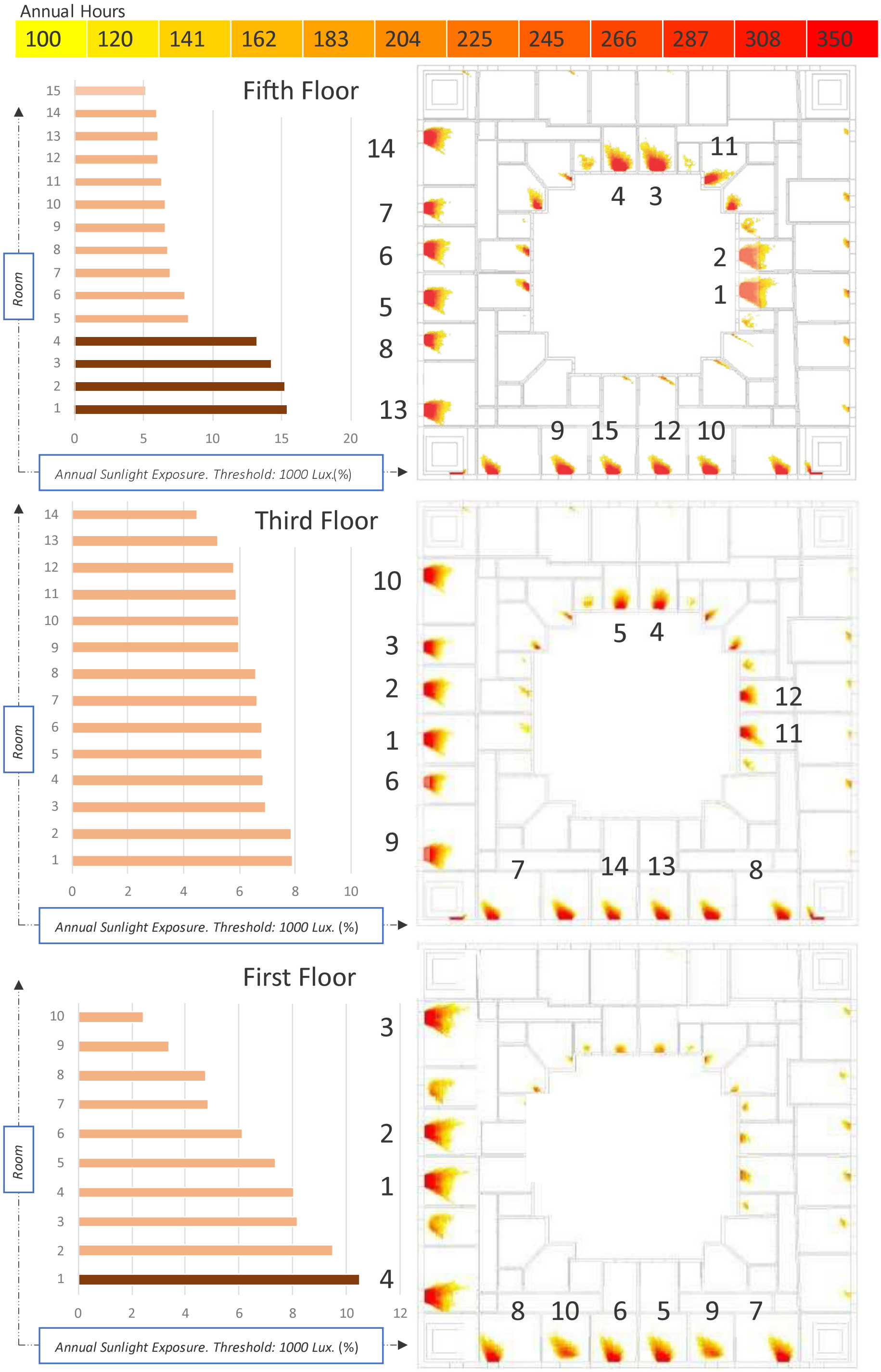

Fig. 9. $ASE_{1000\,lx,250\,h}$ distribution. In each room, percentage of the area in which the illuminance level excess 1000 lux more than 250 h of the occupied hours (08:00-18:00) in a year.

Table 7
Area and percentage in the first, third and fifth floors, respectively, where the requirements of the sDA metric are achieved ($sDA_{300\ lx,50\%}$).

Floor level	First	Third	Fifth
$sDA_{300\ lx,50\%}$ (m^2)	71.8	73.2	104.6
$sDA_{300\ lx,50\%}$ (%)	8.2	8.4	12

inside multiple rooms inside the buildings. Two measures that can be proposed to improve the daylighting performance and utilisation of the case study building to better conform with the lighting criteria established in Table 2 (EN 12464-1:2011, 2011) include:

1. Reallocation of activities of the building to better adapt their use to the required illumination conditions (refer to Section 6.1).
2. Optimisation window-to-wall ratios to improve daylighting performance while considering the impact on overall energy performance (refer to Section 6.2).

6.1. *Reallocation of activities for occupied rooms*

This section evaluates possible modifications to the current functional activities served by the rooms/zones shown in Fig. 11 to improve the visual comfort of the occupant from daylighting.

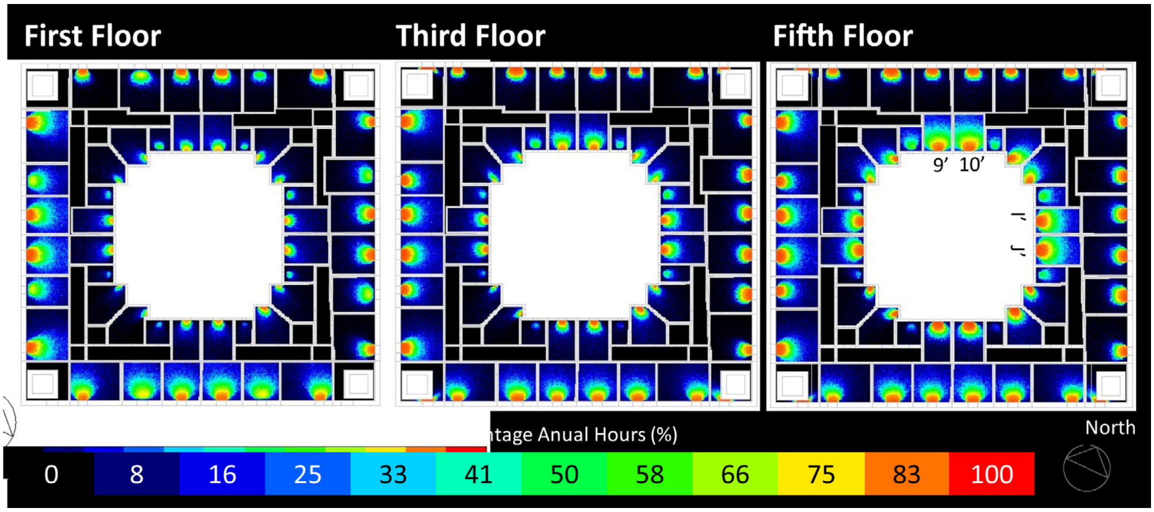

Fig. 10. $sDA_{300\,lx,50\%}$ distribution. Percentage of hours in which the illuminance reaches 300 lux during occupied hours (08:00-18:00) in a year. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

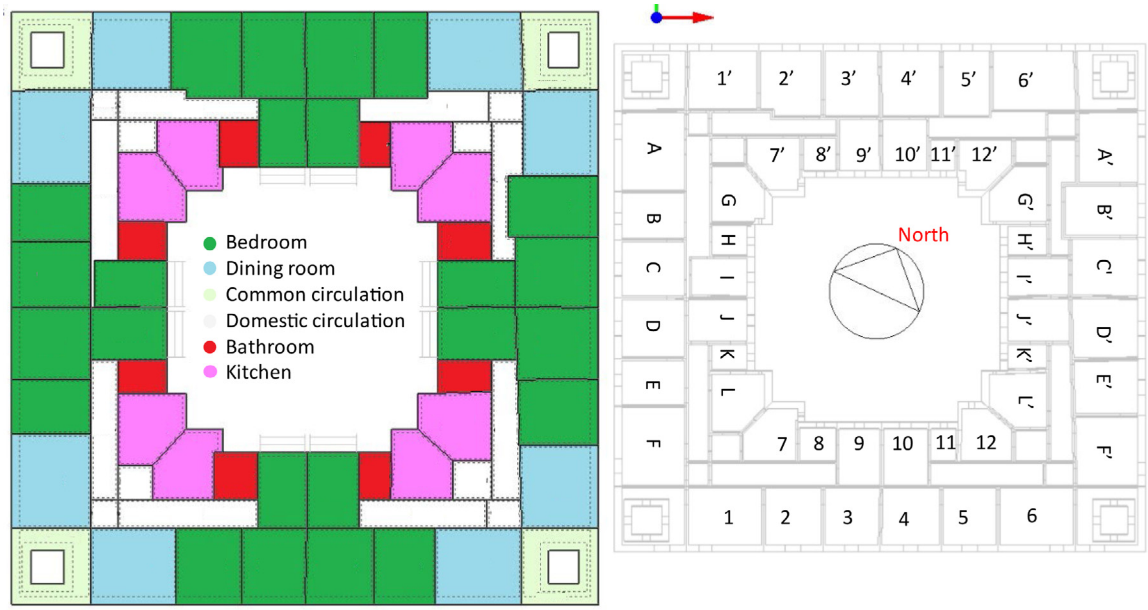

Fig. 11. Division of the housing block according to functional activities. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

6.1.1. *Identification of the rooms best suited as a bedroom, a bathroom or a day room*

Fig. 12 visually shows the $sDA_{200\,lx,50\%}$ of the fifth, third and the first floor for each room to evaluate which rooms can serve activities for which an illuminance of 200 lux is sufficient. Such activities include the bedroom, bathroom, and day rooms. A similar behaviour appears on the outer perimeter of the building, whereby higher lux levels are reported, with much lower intensities in the rooms facing the inner courtyard. Furthermore, Table 8 identifies the percentage floor area for a sample of rooms where the requirements of the sDA ($sDA_{200\,lx,\,50\%}$) is met. Rooms 9, 10, I and J and the rooms facing the opposite orientation (9′ ,10′ , I′ and J′) on the fifth floor show a sufficient lux level to perform the functional activity of a bedroom. However, the first floor will require artificial lighting more often than the upper floors, as evidenced by the sDA results in Fig. 12.

Table 8
Percentage floor area of Rooms 9 and 10, I and J and their opposites (9′,10′, I′ and J′) in the first, third, and fifth floors, where the requirements of the sDA metric are achieved ($sDA_{200\ lx,50\%}$).

Room label	9	10	I	J	9′	10′	I′	J′
First floor (%)	8.6	9.1	9.1	8.5	12.0	12.6	11.0	9.8
Third floor (%)	14.1	15.2	17.1	15.5	24.7	25.9	23.6	21.3
Fifth floor (%)	34.3	35.6	41.1	38.6	60.7	65.9	55.9	55.4

6.1.2. *Identification of the rooms best suited as office or kitchen*

Fig. 13 visually shows the $sDA_{500\,lx,50\%}$ of the fifth, the third and the first floor for each room. This visualisation can better evaluate which rooms can serve activities which require an illuminance of 500 lux, such as offices and kitchens. Furthermore, Table 9 identifies the percentage floor area for a sample of rooms where the requirements of the sDA ($sDA_{500\,lx,\,50\%}$) is met.

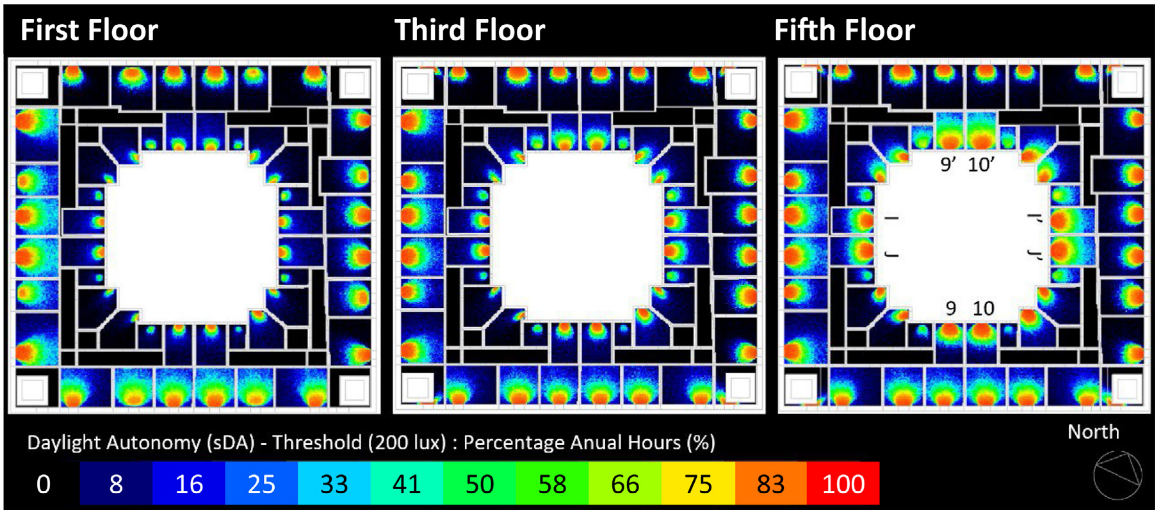

Fig. 12. $\mathrm{sDA}_{200\,\mathrm{lx},\,50\%}$ distribution.

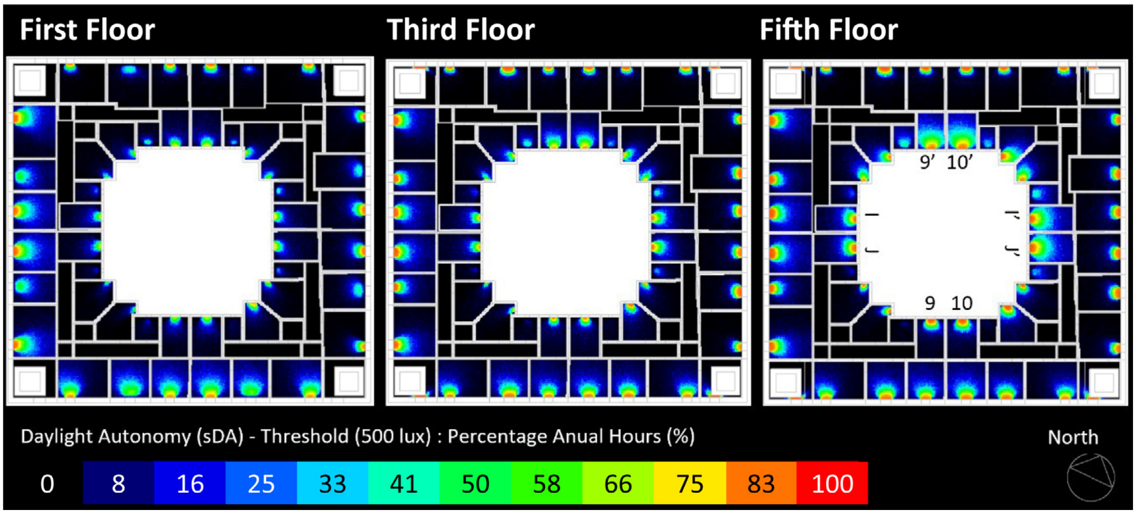

Fig. 13. : $\mathrm{sDA}_{500\,\mathrm{lx},\,50\%}$ distribution.

Fig. 13 shows that the rooms with their external walls exposed to the street-rooms from 1 to 6, 1′ to 6′, and A to F- have adequate lighting levels to be used as kitchens or offices. The room locations with labels A' to F' have a similar pattern when comparing the fifth and the first floor. As expected, the upper floor has a more extensive coverage of 500 lux. For the interior rooms, locations labelled I, J, 9, and 10 (also in I′, J′, 9′, and 10′) show compliant sDA levels. Therefore, these locations are much more suitable for kitchen or study room use. Some apartments have more than one room with good potential in this range.

Table 9 shows the sDA percentages in the kitchens of the building. As can be seen, these rooms require artificial lighting most of the time, even on the fifth floor where the kitchens with the highest $\mathrm{sDA}_{500\ \mathrm{lx},50\%}$ percentages are located. Thus, these kitchen areas will require artificial lighting for more than 85 % of the year.

6.1.3. Identification of rooms best suited as a circulation area

The study of natural lighting in common areas was also carried out, as shown in Fig. 14. First, it should be noted that the common areas for access to the apartments are located at the four corners of the building block and marked in pale green in Fig. 11. Each level has at least one window in the access areas, except for the first floor. The sDA will focus on the fifth floor with the illuminance threshold set between 100 lux ($\mathrm{sDA}_{100\,\mathrm{lx},\,50\%}$) and 150 lux ($\mathrm{sDA}_{150\,\mathrm{lx},\,50\%}$). It is evident that with the existing window sizes, the circulation areas, even on the fifth floor, have very little natural light with an intensity of between 100 and 150 lux achieved only at a very close distance to the window. Therefore, the use of artificial lighting for common areas is usually required. One solution could be introducing solar tubes or fibre optic systems to bring natural light from the roof level to each floor.

Table 9
Percentage of each kitchen area on the first, and fifth floors, where the requirements of the sDA metric are achieved ($\mathrm{sDA}_{500\ \mathrm{lx},50\%}$).

Kitchen label in Fig. 11	7	12	7′	12′	G	L	G′	L′
First floor (%)	0.9	4.0	1.3	2.2	0.6	0.5	1.3	1.3
Third floor (%)	1.3	5.6	2.1	4.2	1.4	1.3	2.8	1.8
Fifth floor (%)	3.7	10.3	5.9	15.2	4.7	2.5	8.2	4.0

6.1.4. Results of the reallocation of activities for occupied rooms

The study of natural lighting in common areas for different illuminance levels (100, 150, 200, and 500 Lux) has been obtained

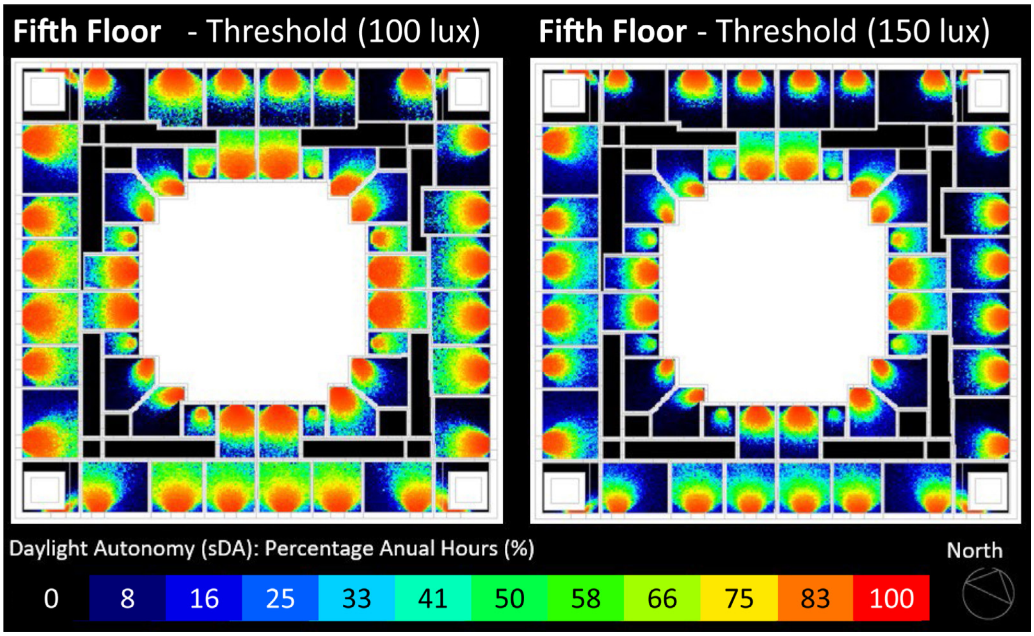

Fig. 14. $\mathrm{sDA}_{100\,\mathrm{lx},50\%}$ and $\mathrm{sDA}_{150\,\mathrm{lx},50\%}$ distribution.

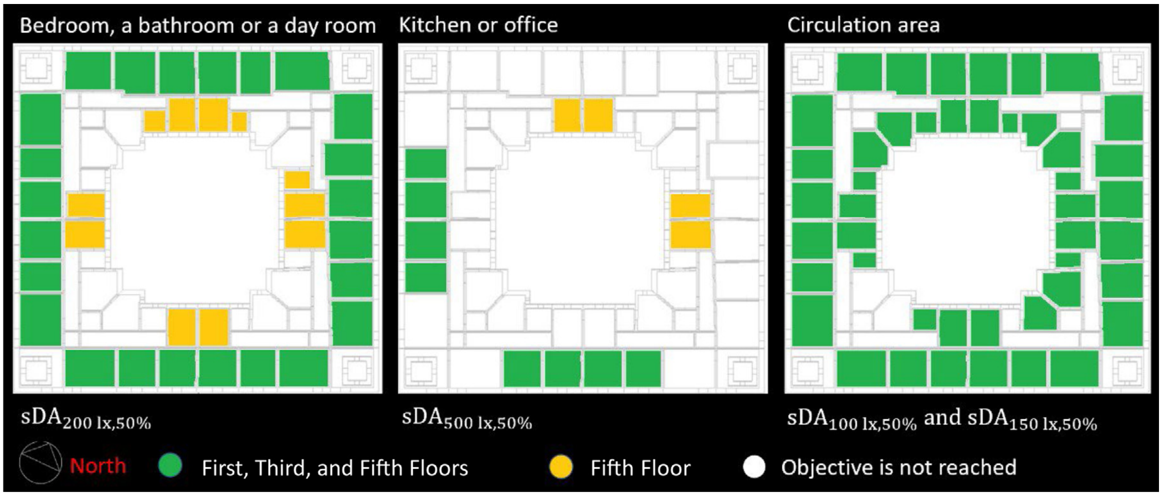

Fig. 15. Identification of rooms best suited to serve as Bedroom, a bathroom or a day room, kitchen or office and circulation area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and shown in Figs. 12–14. As can be seen, specific spaces in the dwelling are suitable for its use as a bedroom, bathroom or day rooms, kitchen or office and circulation area. Fig. 15 shows the rooms with acceptable conditions for those uses in green or yellow. It is observed that the current position of the kitchens does not satisfy the minimum requirements for natural lighting ($\mathrm{sDA}_{500\,\mathrm{lx},\,50\%}$). On the other hand, almost all rooms serve as circulation areas following the $\mathrm{sDA}_{100\,\mathrm{lx},\,50\%}$ and $\mathrm{sDA}_{150\,\mathrm{lx},\,50\%}$ criteria, respectively. Finally, all rooms with an outdoor window serve as a bedroom, bathroom, or day room ($\mathrm{sDA}_{200\,\mathrm{lx},\,50\%}$).

6.2. Window-to-wall ratio (WWR) optimisation

While the $\mathrm{ASE}_{1000\,\mathrm{lx},250\,\mathrm{h}}$ evidenced that the original design of the housing falls in the preferred range, the $\mathrm{sDA}_{300\,\mathrm{lx},\,50\%}$ metric did not reach the recommended range, as shown in Table 7. As changes in orientation and design at the renovation stage are not possible, modification of the size of the windows is suggested as an improvement measure. Increasing the size of specific windows would allow reaching the nominally accepted range ($55\,\% < \mathrm{sDA}_{300\,\mathrm{lx},\,50\%} < 74\%$), while the glare risk will be kept within the acceptable range ($\mathrm{ASE}_{1000\,\mathrm{lx},250\,\mathrm{h}} < 10\%$). This study is carried out on the first floor where the sDA (Table 7) and UDI-A (Table 5) criteria show the worse score. Four configurations for the window-to-wall ratio (WWR), shown in Fig. 16 and explained below, are analysed in addition to the current WWR scenario (Model 1). These designs aim to improve daylighting potential in terms of daylighting autonomy. The models under consideration are:

- Model 2 increases the WWR of the rooms facing the inner courtyard by 50%.
- Model 3 increases the size of the fenestration glazing facing the inner courtyard and the fenestration glazing in the outer rooms of zones 2 and 4 facing the street to a WWR of 100%. The WWR for the glazing fenestration in the other rooms is left intact.
- Model 4 increases the size of the fenestration glazing facing the inner courtyard and the fenestration glazing in the outer

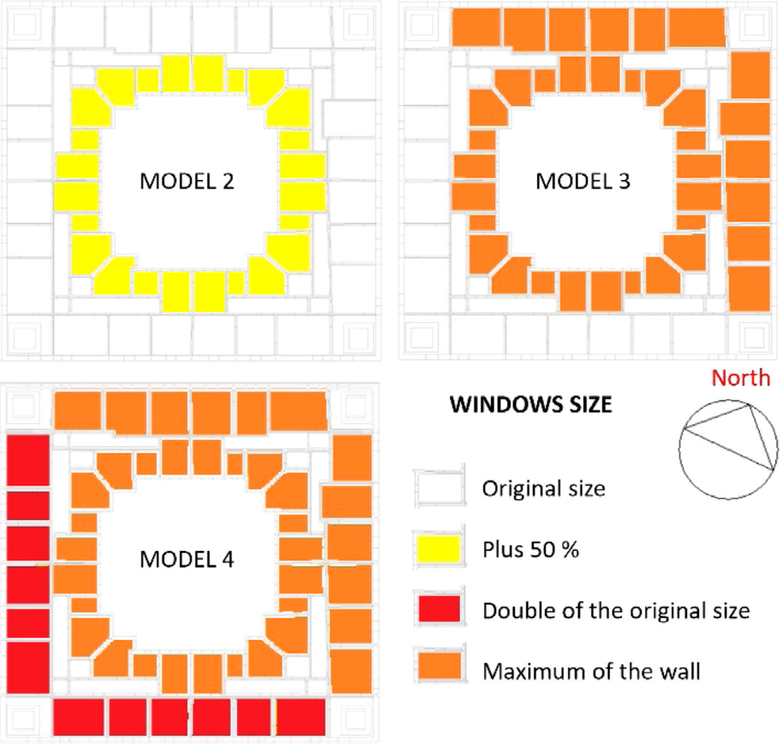

Fig. 16. Three proposals for the modification of the original windows size of the first floor.

rooms of zones 2 and 4 facing the street to a WWR of 100%. The WWR for the glazing fenestration in the other rooms is doubled.

In addition to increasing the WWR, two other glazing configurations were studied. While Models 3 and 4 focus only on improving the daylighting autonomy of the building, Models 5 and 6 consider a more holistic and optimal approach to energy modelling. This is done by aiming to find the best balance between increasing the daylight autonomy of the building while keeping the potential additional heating/ cooling loads and glare brought about by the increased WWR in Model 4 to a minimum. This is achieved using the same WWR configuration as in Model 4 but simulating Models 5 and 6 with different glazing technologies to alter the glazing U-value and Solar Heat Gain Coefficient (SHGC).

- Model 5 includes a spectrally selective film (model 3M PR70), 3M Science Applied to Life (2017) on the outer window pane's external surface. The film aims to reduce the potential risk of increased glare and summer cooling loads due to more direct solar radiation penetrating the windows. While Models 1 to 4 employ single glazing with a U-value of 5.8 W/m^2 K, SHGC of 0.82 and light transmittance of 0.88, Model 5 glazing has a U-value of 5.5 W/m^2 K, SHGC of 0.46 and light transmittance of 0.61.
- Model 6 is the same as model 5 above, having the spectrally selective film on the outer windowpane's external surface but replacing the single glazing with double glazing technology with an air gap between the two panes. The final glazing properties for Model 6 are a U-value of 3.2 W/m^2 K, SHGC of 0.36 and light transmittance of 0.55.

The results of the analysis of the proposed models are shown in Fig. 17. As can be seen, for all models 2 to 6, the $\mathrm{sDA}_{300\,\mathrm{lx},\,50\%}$, and $\mathrm{UDI}_{300-3000\,\mathrm{lx}}$ metrics have improved concerning the original glazing configuration (Model 1). Model 4 has the best-improved performance compared to the other models in terms of $\mathrm{sDA}_{300\,\mathrm{lx},\,50\%}$ and $\mathrm{UDI}_{300-3000\,\mathrm{lx}}$, while still complying with $\mathrm{ASE}_{1000\,\mathrm{lx},250\,\mathrm{h}}$. Model 4 is also the only model that fully complies with the acceptable ranges for $\mathrm{sDA}_{300\,\mathrm{lx},\,50\%}$. Models 3, 5 and 6 provide similar performance in terms of $\mathrm{sDA}_{300\,\mathrm{lx},\,50\%}$ and $\mathrm{UDI}_{300-3000\,\mathrm{lx}}$ with improvements of up to 400% compared to Model 1, and only inferior to Model 4 by approximately 25%. While all models are compliant with the acceptable $\mathrm{ASE}_{1000\,\mathrm{lx},250\,\mathrm{h}}$ range, the best performance is shown by the model configurations with the lowest WWR (model 1 and model 2), and the glare risk increases as the WWR increases.

Based on the SDA, UDI and ASE results as depicted in Fig. 17 for Models 5 and 6 when compared to Model 4, the potential of reducing glare following the $\mathrm{ASE}_{1000\,\mathrm{lx},250\,\mathrm{h}}$ metric is minimal by adding a spectrally selective film to the glazing or upgrading to double glazing. Thus, the impact that these technologies have in lowering the SDA and UDI is larger than their potential to minimising glare in accordance with the $\mathrm{ASE}_{1000\,\mathrm{lx},250\,\mathrm{h}}$.

However, to identify the model best suited for the first floor, one needs to look at the overall comfort and energy performance requirements of the building in line with the new EPBD and, more specifically, the latest EPB standards. Based on the combined results of the considered lighting metrics and the space cooling/heating energy demand and load requirements shown in Fig. 17 and Table 10, Model 4 provides the best performance of daylighting autonomy. However, this benefit comes with the repercussion of increasing the annual cooling energy demand by 935% and the annual heating demand by 20% compared to Model 1. The results for Model 3 are similar to Model 4 in terms of overall cooling and heating performance.

In contrast, Model 5 and Model 6 show a better performance for space heating and cooling when compared to models 3 and 4. Model 6 provides the best overall space heating and cooling performance compared to the other models with the same WWR. The latter results because the spectrally selective coating reduces the cooling loads from solar radiation in summer, while the double glazing reduces heat loss via conduction during winter.

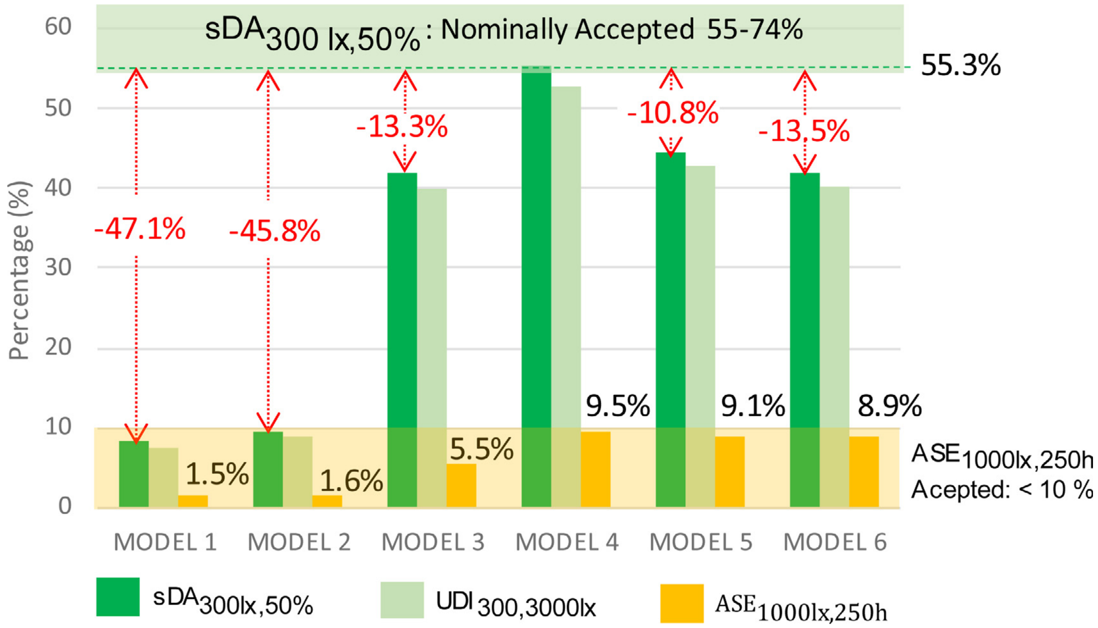

Fig. 17. Comparison of the proposed design models versus the original one considering the indices $sDA_{300\,lx,\,50\%}$, $ASE_{1000\,lx,250\,h}$, and $UDI_{300-3000\,lx}$, for the area of the first floor.

Thus, when compared to Model 4, Model 6 reduces the space cooling energy demand by more than 75% and the space heating demand by almost 9%. However, compared to the original model (Model 1), the annual cooling demand is still 193% larger for Model 6, while the heating load is only minimally increased.

This means models 3 and 4 provide the best daylighting performance in terms of SDA and UDI but the worst overall heating and cooling performance. On the other hand, model 6 shows only a 10% reduced performance in SDA and UDI compared to models 3 and 4, but a much better overall space heating and cooling performance. Thus, the two models that one should carefully consider are Model 1 (the original model), having the best performance in space heating and cooling, and Model 6, which has an inferior space cooling performance (by 193%) but a better performance in SDA and UDI metrics (by more than 400%).

Thus, based on these results and considering various economic factors, social factors and the overall well-being of the occupants described below, in line with the renovation wave for Europe, Model 1, which has glazing areas compliant with the minimum technical requirements for Malta, should be retained. The economic factors considered for this choice include the high cost of the retrofitting measure to increase the façade WWR and the emergence of highly efficient LED lighting technology, making space heating and cooling more critical than daylighting in combatting energy poverty. Furthermore, the social factors considered include increased issues of privacy and glare with larger glazing areas.

Research in state-of-the-art materials has generated a wide variety of glazing technologies with good thermal and acoustic properties (Cuce et al., 2016; Cuce and Riffat, 2015; Moretti et al., 2017). In double-glazed systems, the choice of filler gas can greatly improve the thermal performance of the window (Cuce, 2018). However, some of these technologies decrease the transparency of the material, worsening the interior visual comfort (Cuce, 2018; Cuce et al., 2016; Cuce and Riffat, 2015; Moretti et al., 2017). As the results summarised in Fig. 17 and Table 10 have shown, model 6 achieved a decrease in cooling and heating demand, without excessively penalising the contribution of natural light.

Table 10
Energy demand, heating and cooling loads power, and thermal comfort indicators.

	Model	1	2	3	4	5	6
Energy demand (kWh)	Heating	5418	5484	6414	6128	7476	5582
	Cooling	291	337	2888	3012	1449	853
Loads (kW)	Heating	44	45	55	57	56	45
	Cooling	3	4	22	24	14	10

7. Conclusions

This study reviewed different lighting parameters that need to be considered in the design or refurbishment stage of buildings to enhance the potential of natural lighting while improving its overall energy performance. In addition, these parameters also bring about other non-measurable benefits, such as better indoor ambience and a positive impact on health and well-being. These factors are increasingly being considered even within the new EU energy performance of buildings directive and its forthcoming recast.

A case study of a social housing block was used to evaluate the potential use of natural lighting of a Housing Block in a Mediterranean climatic setting. For this purpose, the Daysim simulation engine in DesignBuilder was used to assess the natural lighting potential of the case study building. The model was calibrated hourly using actual measured data collected by a calibrated lux meter and following the recommendations of the ASHRAE Guideline.

The initial approach focused on the current indoor daylight quality of the building and pointed out the following issues:

1. Firstly, the $UDI_{100-500\,lx}$ was used to quantify the area that reaches the recommended UDI levels for human activity, and together with the $UDI_{300-3000\,lx}$ (defined as the percentage area in which the natural light is sufficient for avoiding the use of artificial lighting), were evaluated for the first, third and fifth floors. The values of $UDI_{100-500\,lx}$ and $UDI_{300-3000\,lx}$ were too low, at best reaching 34.8% and 11.1% of the floor area, respectively, and this demonstrated unsatisfactory low daylight contribution.

2. Secondly, the analysis of $\text{ASE}_{1000\,\text{lx},250\,\text{h}}$, and $\text{sDA}_{300\,\text{lx},50\%}$ allowed the analysis of the building in the context of international recommendations. Good results were derived from the $\text{ASE}_{1000\,\text{lx},250\,\text{h}}$ study, as less than 2.7% of the total area of each floor is affected by glare, and this which percentage was shown to increase with height. Besides, only 15 rooms on the fifth floor exceeded the $\text{ASE}_{1000\,\text{lx},250\,\text{h}}$ optimum values, while only four rooms were more than the acceptable range. However, the analysis of the $\text{sDA}_{300\,\text{lx},50\%}$did not reach the international recommendations.

As this study has highlighted, the original design fails to offer good lighting levels with low $\text{sDA}_{300\,\text{lx},50\%}$, $\text{UDI}_{300-3000\,\text{lx}}$, and $\text{UDI}_{300-3000\,\text{lx}}$ values. Two procedures to enhance its daylight potential were proposed:

1. First, several combinations of sDA maps proposed appropriate reallocation of rooms in line with their minimum light requirements according to the European standard EN 12464-1. It must be pointed out that $\text{sDA}_{300\,\text{lx},50\%}$ map demonstrates that the position of the kitchen is not ideal when it comes to the amount of natural lighting that it enjoys. Moreover, the common areas where the stairs and the lift are situated at the four corners of the building block, do not receive a minimum amount of natural lighting as the sDA threshold between 100 and 150 lux showed. This finding necessitates the re-consideration of the internal reallocation of rooms, given that the building will be undergoing a major renovation. Trying to match the use of the room to the available natural light level will contribute towards the reduction of artificial lighting and overall better energy performance of the building. On the other hand, the other rooms demonstrated to have sufficient sDA values that are adaptable for different purposes, such as 200 lux (general uses, $\text{sDA}_{200\,\text{lx},50\%}$) and 500 lux (office uses, $\text{sDA}_{500\,\text{lx},50\%}$).
2. Second, the improvement of the $\text{sDA}_{300\,\text{lx},\,50\%}$ and $\text{ASE}_{1000\,\text{lx},250\,\text{h}}$ according to international recommendations were studied. It was found that the first floor windows overlooking the internal yard would need to be enlarged to allow more natural lighting to pass through. Therefore, different design alternatives, models 2 to 6, were proposed. The increase in specific window sizes allows the daylighting level to satisfy the accepted ranges of $\text{sDA}_{300\,\text{lx},\,50\%}$ and $\text{ASE}_{1000\,\text{lx},250\,\text{h}}$, simultaneously.
   Model 4 provides the best performance, comparing $\text{sDA}_{300\,\text{lx},\,50\%}$ and $\text{UDI}_{300-3000\,\text{lx}}$, but it is slightly lower than the accepted limit of $\text{ASE}_{1000\,\text{lx},250\,\text{h}}$. Model 3 has around 10% lower performance in $\text{sDA}_{300\,\text{lx},\,50\%}$ and $\text{UDI}_{300-3000\,\text{lx}}$ indices. Nevertheless, it keeps the $\text{ASE}_{1000\,\text{lx},250\,\text{h}}$ in the range of neutrality. In addition, models 3 and 4 notably increment the $\text{UDI}_{300,3000\ \text{lx}}$ index. About 40% of the first floor area meets the $\text{UDI}_{300-3000\,\text{lx}}$ for half of the occupied hours (08:00-18:00) for model 3 and 52.8% for model 4, respectively.
   On the other hand, Model 2 did not improve the original model sufficiently. Models 5 and 6 have extra layers that decrease the energy losses but reduce the time the housing block verifies the criteria of adaptive comfort (EN15251) in the summertime.
   In conclusion, while model 4 provides the best daylight performance (highest $\text{UDI}_{300-3000\,\text{lx}}$, $\text{ASE}_{1000\,\text{lx},250\,\text{h}}$, and $\text{sDA}_{300\,\text{lx},50\%}$), it does increase the energy demand for heating and cooling. Therefore, the recommendation would be to consider model 6 as the most balanced design, as despite inferior daylight performance, it has a much lower energy demand for heating and cooling.

This study has shown a wide margin for improvement in the use of daylight in residential buildings. A previous analysis of the natural lighting conditions in the design stage of the building would have enabled a better determination of the most appropriate arrangement of the main rooms to improve the residents' visual comfort, well-being and energy performance.

CRediT authorship contribution statement

Diego Granados-López: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Original draft preparation, Writing – review and editing, Visualization. **Damien Gatt:** Methodology, Validation, Formal analysis, Writing – review and editing, Supervision. **Charles Yousif:** Conceptualization, Writing – review and editing. **Montserrat Díez-Mediavilla:** Validation, Writing – review and editing, Supervision, Project administration. **Cristina Alonso-Tristán:** Validation, Writing – review and editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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