

Article

# Daylight Provision Requirements According to EN 17037 as a Restriction for Sustainable Urban Planning of Residential Developments

Nataša Šprah <sup>1,\*</sup> and Mitja Košir <sup>2</sup> 

<sup>1</sup> Department of Architecture, Faculty of Civil Engineering, Transportation Engineering and Architecture, University of Maribor, 2000 Maribor, Slovenia

<sup>2</sup> Department of Buildings and Constructional Complexes, Faculty of Civil and Geodetic Engineering, University of Ljubljana, 1000 Ljubljana, Slovenia; mitja.kosir@fgg.uni-lj.si

\* Correspondence: natasa.sprah@um.si

Received: 17 December 2019; Accepted: 28 December 2019; Published: 31 December 2019



**Abstract:** The attempt at a more sustainable land use by increasing urban density may have a negative effect on the daylighting of residential buildings. In densely built areas, obstructions generated by the surrounding buildings can substantially reduce the available amount of daylight, causing poorly daylit spaces and a less healthy indoor environment with higher electricity consumption as a consequence of artificial lighting. European standard EN 17037, Daylight in Buildings, was established in 2018 to ensure appropriately daylit spaces. In this paper, a three-step methodology was developed to investigate the relationship between certain urban planning parameters and the daylighting of a typical room defined by specific (Slovenian) legislative restrictions about its geometry and minimum required window to floor area ratio, in order to establish the maximum densities of residential developments still fulfilling the minimum requirements for daylight provision defined by EN 17037. The results show that a relatively low urban density is required to fulfil the stipulations for minimum daylight provision for the deepest permissible room according to the Slovenian legislation. The impact of the development floor area ratio on the daylighting potential of buildings was identified as significant, followed by the site coverage, development layout, and building typology. Furthermore, the developed methodological approach clearly demonstrates a substantial potential for application in urban planning, with indoor daylight environmental conditions being linked to the planning of residential developments in the earliest stages of the project.

**Keywords:** sustainable urban planning; daylighting; vertical daylight factor; EN 17037; residential developments; solar potential

## 1. Introduction

Cities are among the most important entities shaping the sustainable future of human well-being [1]. In this regard, compactness of the built environment is a widely acceptable strategy through which more sustainable urban forms might be achieved [2]. Positive effects of urban densification as a strategy for sustainable development, such as the reduction of energy needs for heating, cooling and mobility as well as the possibility for more efficient land use, have been widely accepted and adapted to various policies [3]. Additionally, residential density improvement can significantly decrease carbon emissions [4]. However, the most appropriate urban form and density in the case of achieving lower energy consumption are different from the targets of the highest economic benefits or social sustainability [5]. Within the social aspect of the sustainability agenda, urban form works in different ways—density can for example worsen social equity [6].

In terms of daylighting, high urban densities portend a decrease in the amount of natural lighting of occupied spaces in the interior of the buildings, which has proven to have negative health effects on their occupants [7]. Insufficient daylight in residential buildings is associated with depression [8], sleep disruption as well as higher occurrence of cancers [9,10]. To the contrary, higher levels of light exposure stimulate physical activity and longer sleep duration [11]. The significance of light as an essential element of healthy living has been emphasized by the recent discovery of a specialized photoreceptor in the eye responsible for synchronizing our internal circadian pacemaker [12], thus highlighting the importance of basing housing design upon the amount of daylight available for maintaining synchronization of the human circadian system [13]. Furthermore, numerous studies have shown the significance of utilizing daylight in buildings for saving energy [14,15], identifying daylighting as a crucial element in architectural design and a useful strategy for energy-efficient building designs. As in the European Union residential buildings make up to 75% of the building stock [16], and research shows we spend more than 13 h per day inside them [17], thus the impact of properly daylit indoor spaces is significant [18].

Standards and regulations about daylight in buildings are imperative for setting minimal acceptable conditions for indoor natural lighting. As in numerous other European countries [19], minimum solar exposure, expressed in hours, is prescribed also in Slovenia. The Technical Guideline, TSG-1-004:2010—efficient use of energy [20] requires that the “collecting area” (the roof and the facade) of a building is exposed to sun’s rays 1 m above the ground (lower areas are not considered due to natural and built obstructions) at least 2 h on 21st of December, on the equinoxes (21st of March and September) at least 4 h, and at the summer solstice (21st of June) at least 6 h. The second requirement for the daylighting of rooms in residential buildings in Slovenia stems from the rules on minimum technical requirements for the construction of apartment buildings and apartments [21]. According to the stated rules, minimum natural lighting is achieved when the openings of a room have a surface of at least 20% of the room surface (i.e., window-to-floor ratio of 20%). Additionally, there is a limit to the depth and width of one-sidedly lit rooms. The requirements of the Rules do not consider the actual coincidence of daylight on the building envelope, thus disregarding the effect of overshadowing from neighboring buildings, greenery and orientation. In 2019, the new European standard Daylight in buildings, EN 17037, was adopted as a Slovenian national standard [22]. This standard encourages building designers to design, assess and ensure sufficiently daylit spaces. According to EN 17037, there are four criteria for the assessment of daylight in interior spaces: Daylight provision, view out, exposure to sunlight and protection from glare. While the standard gives exact instructions on how to test detailed building designs with regards to the four stated criteria, it is less applicable during the early design stages, where the optimization of the urban plan in terms of daylight and overshadowing by neighboring buildings is of foremost importance.

The insolation of buildings in an urban context has been explored abundantly [23]. However, the emphasis has been placed mostly on the amount of solar irradiation falling on the building envelope. In this way, the potential for active and passive solar systems at different locations could be assessed, or the compliance with standards and/or legislation in terms of mandatory hours of building envelope insolation could be tested. In well-cited research of solar and daylight availability in the urban fabric performed by Compagnon [24,25], a method of quantifying the potential of facades and roofs of buildings for active and passive solar heating, photovoltaic electricity production and daylighting was presented. The link between urban design and energy planning was examined in a parametric typological study conducted at a block scale in the context of Tel Aviv [26], where the energy cooling loads, spatial daylight autonomy and the monthly average load match between energy demand and photovoltaic energy supply were the environmental outputs. Among other findings the study established that the effect of urban density on environmental performance could be clearly seen in all typologies; in higher densities, mutual shading between buildings reduces the energy load match mostly due to the reduction in PV energy generation on facades; moderate reductions in cooling energy demand due to self-shading were not sufficient to balance energy generation reductions. The

different effects of horizontal and vertical randomness of urban layout on the solar potential have been investigated previously [27], demonstrating that at the same floor area ratio (FAR), models with low site coverage and horizontally and vertically random distribution show a higher solar potential. A study about solar urban planning recommendations to enhance the solar accessibility in a Nordic urban environment [28] also demonstrated that by optimizing the urban morphology and choosing the finishing materials during early design phases, the solar potential can be increased by up to 25%. In the context of Slovenia, the solar potential of the existing building stock in terms of minimum solar exposure of the building envelope was examined previously [29]. The findings demonstrated that the existing layouts are not as problematic as expected. On the contrary, recently densely built layouts, the ones considered as examples of infiltration of global liberal economy, are those that will probably present a future challenge due to the limited solar potential of such buildings. This is predominately caused by diminished distances between buildings and increased urban densities, inducing a non-linear increase of mutual shading due to shadows cast by the neighboring buildings.

In recent years, the number of studies about daylight on the urban scale has increased [30]. Vertical daylight factor (VDF) has been explored as a criterion for the evaluation of natural lighting potential of buildings by comparing the VDF calculation method to other simulation techniques [31]. A study of an urban canyon [32], in which the relationship between the exterior illuminance levels on the facade surface and the interior illuminance levels on the working plane was examined via daylight factor (DF) and VDF [33] demonstrated that VDF would decrease with smaller street widths and higher opposing buildings. Furthermore, it is evident that increased facade reflectance of the opposing building would result in slightly higher VDF levels and could result in more rays bouncing off from that building and more of the light penetrating deeper into the room in question. This study was later expanded by Iversen [34] comparing the above-mentioned metrics with the Daylight Autonomy climate-based dynamic daylighting metric. The impact of urban density on daylight and passive solar gains was also explored by Strømman-Andersen and Sattrup [35] who applied climate-based dynamic thermal and daylight simulations in order to study how these are affected by increased urban density. However, the last four stated studies were limited to urban canyons and did not consider other urban morphologies and architectural typologies. A paper by Zhang et al. [36] proposed a daylight performance indicator for urban analysis: facade VDF per unit of floor area. A numerical simulation was conducted across multiple generic forms and different density scenarios. The results showed a strong positive correlation between the proposed indicator and the reference indicator of interior daylight potential. Recently, a research on daylight regulation compliance of existing multi-family apartment blocks in Sweden has been conducted by assessing DF in rooms of various architectural typologies. It indicated that certain typologies regularly yield poor DF levels and showed a moderate correlation between the density of the surrounding urban area and the percentage of rooms compliant with the regulation [37].

In regard to the above-presented context, this research considers daylighting potential of urban models, based on the attributes of recent residential developments in Slovenia. The objective is to define an approach that can be used as a meaningful tool to determine guidelines regarding maximum allowable residential development densities, preferred building typologies and urban morphologies in the early planning stages. The proposed approach directly associates the characteristics of the urban plan with the daylighting quality of the buildings' indoor environment. In this way, the sustainability aspects of future residential developments are concurrently addressed on the level of urban plan as well as on the level of the quality of indoor environment. This is a marked improvement on the current practice of prescribing minimum duration of the building envelope insolation [38], with unknown consequences for the daylighting conditions of the buildings' interior, or prescribing the minimum window-to-floor area ratio (WFR) or window-to-wall ratio (WWR) while disregarding the impact of the surrounding built environment (i.e., shading).

## 2. Methodology

As stated in the introduction, the objective of this study was to formulate a methodology for urban planning recommendations (i.e., guidelines) of residential developments based on daylighting requirements for occupied residential rooms, as stipulated in EN 17037. Although the requirements of the stated standard are not directly applicable to urban planning, they can be applied indirectly. This can be achieved by linking the daylighting of a typical room defined by specific legislative restrictions about its geometry and minimum required area of windows to the overall insolation and daylight potential of a building in the context of a specific urban setting. The proposed relationship can then be used to define guidelines regarding maximum urban densities that still allow for the minimum required daylighting of indoor spaces at the stage of urban planning prior to the commencement of detailed architectural design. The main advantage of the proposed approach to the urban planning of residential developments is in the way indoor daylighting requirements are already considered at the urban level and therefore contribute to better indoor living conditions and, at the same time, to sustainable land use. In order to achieve the stated objective, the presented study implemented the following three phases (Figure 1):

- Step 1: Analysis of daylight provision in rooms by calculating the daylight factor (DF) and linking it to the average vertical daylight factor ( $VDF_{avg}$ ) calculated on the facade surface of the analyzed room. In this way, the threshold minimum average values of  $VDF_{avg}$  at which the interior of the room is lit according to the requirements of EN 17037 are established;
- Step 2: Definition of appropriate residential development simulation models, based on typical characteristics of the selected test examples of two multi-residential typologies (i.e., mid-rise point and linear buildings). Each defined and simulated residential development is comprised of nine buildings, with the central one being the analyzed building, representing the worst-case scenario. The calculation of  $VDF_{avg}$  of each individual story facade section of the central building consequentially enables the analysis of the correlation between  $VDF_{avg}$  and residential development formation parameters;
- Step 3: Identification of the correlation between the daylight potential of the observed building (interior DF) and the studied residential development formation parameters. The goal is to define parameters that can be used as guidelines for the determination of maximum allowable residential development densities at an early planning stage.

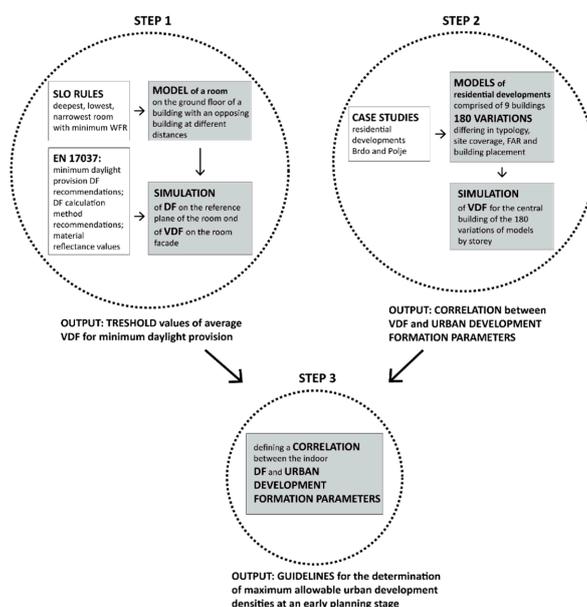


Figure 1. Structure of the research procedure.

The three-step method for establishing the association between DF in the interior of the room and  $VDF_{avg}$  on the facade (instead of modelling the rooms directly in the specific residential development models) was chosen to eliminate the effect of the specific position of the room in the building floorplan on the acquired results. Parts of the method have been used in previous studies. Specifically, the method of linking VDF on the facade to DF in the room has been employed before by Iversen et al. for the investigation of urban canyons [33], while the urban geometric model of nine buildings, with the central one being analyzed, has been used in a study about solar accessibility by Lobaccaro et al. [28].

The simulations were conducted by combining the Rhinoceros 3-D modelling tool [39] with the algorithmic modelling tool Grasshopper [40] to control the generation and modification of geometric parameters. The calculation of the daylighting parameters was executed using the daylighting and energy modelling plug-in DIVA-for-Rhino [41], which is a validated Radiance-based software that enables modelling of the annual amount of daylight in and around buildings [42]. DF and VDF calculations were conducted with Radiance settings, presented in Table 1.

**Table 1.** Radiance settings used in the conducted analysis.

ambient accuracy	ambient bounces	ambient divisions	ambient resolution	ambient super-samples	direct relays	source substructuring
0.1	7	4096	512	1024	2	0.2
limit reflection	limit weight	direct certainty	direct pretest density	direct thresholding	mist sampling distance	specular threshold
12	0.001	0.75	2048	0.05	0.063	0.01

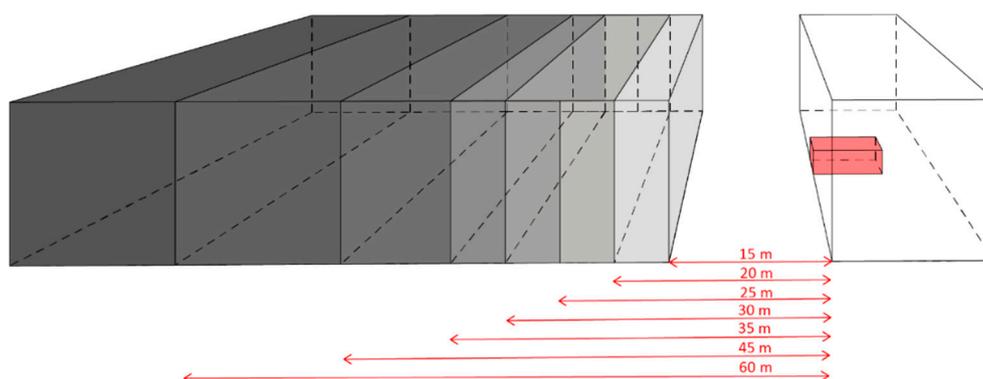
The selected location for the executed calculations was Ljubljana, Slovenia (latitude: 46°03' N, longitude: 14°30' E). Therefore, the necessary weather file was sourced from the EnergyPlus website [43].

### 2.1. Step 1: Procedure for Connecting the Achieved DF in the Room to the $VDF_{avg}$ on the Facade

According to EN 17037, there are four criteria for the assessment of daylight in interior spaces: daylight provision, view out, exposure to sunlight and protection from glare. As the current study aims to examine daylight in rooms in an urban context in order to establish the maximum densities of residential developments, only the minimum daylight provision criteria were examined. The criteria for daylight provision in EN 17037 state that a space is considered adequately daylit if the target illuminance levels are achieved across a fraction of a reference plane within a space for at least half of the daylight hours. There are two methods for calculating daylight provision; the first one presumes the calculation of DF on the reference plane, with defined values for target and minimum DF to be achieved depending on the given location. The second option is calculating the illuminance levels by using the climactic derived illuminance data and an adequate time-step. The DF approach is simpler, as it is based on the CIE overcast sky and, therefore, does not include the influence of the direct sunlight, which consequently also means that window orientation has no effect on the resulting DF values. Although the DF method is not completely reliable in predicting the actual daylight performance, and using a single daylighting metric is unlikely to result in a better daylight environment [44], it is appropriate for testing conformity to minimum requirements, which would include overcast sky conditions [45]. Therefore, the current study utilizes the first method with the DF values recommended by EN 17037 for the location of Ljubljana, the Slovenian national capital.

In order to establish the minimum average VDF on the facade of the building for its interior to comply with the daylighting requirements of the EN 17037 standard, the daylight provision for a model of the deepest, lowest and narrowest room permissible according to the Slovenian Rules on minimum technical requirements for the construction of apartment buildings and apartments [21] was modelled. Specifically, this means that a room of  $3.75 \times 7.50 \times 2.50$  m (w  $\times$  d  $\times$  h) was placed on the ground floor and in the center of a 45 m long and 15 m high building. The exterior facade wall was

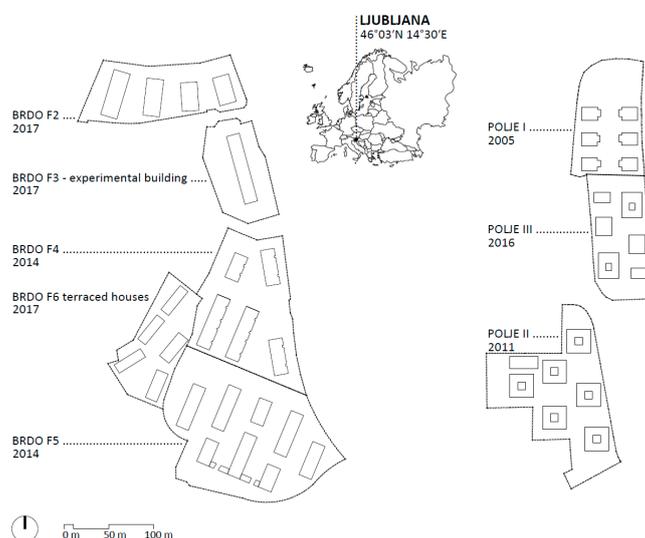




**Figure 3.** Addition of an opposing building at various distances to reduce the  $VDF_{avg}$  and the amount of daylight in the modelled room.

## 2.2. Step 2: Defining the Correlation between $VDF_{avg}$ on the Facade and Urban Planning Parameters

Simplified models of residential developments were defined in accordance with the characteristics of the recently constructed developments. Brdo [46] and Polje [47] in Ljubljana, Slovenia (Figure 4). These were chosen as case studies on the grounds of being the largest publicly funded housing developments recently built in Slovenia, with their design stemming from public architectural competitions. Brdo is an example of a mid-rise development of linear residential buildings, while Polje incorporates different forms of mid-rise residential point buildings (Figure 4). Both developments were built in phases, Polje between 2005 and 2016 and Brdo between 2014 and 2017. For the purpose of the presented study, selected phases of each of the two residential developments were used to define archetypical urban geometric configurations. Specifically, Polje I, II and III, and Brdo F4 and F5 (Figure 4) were selected as sources for point and linear building residential development configurations, respectively.



**Figure 4.** Site plans of housing developments Brdo (left) and Polje (right) used for the definition of simplified generic models discussed in the study.

The chosen residential development characteristics are presented in Tables A1 and A2 in the Appendix A. The analysis included building dimensions, number of story's, distances between the buildings and placement of buildings with respect to one another as well as site coverage (i.e., the ratio between the area covered by the ground floor of the building and the area of the site) and FAR (floor area ratio—the ratio of a building's total floor area to the area of the site). Average values for

each of the mentioned parameters thus obtained were adjusted—the dimensions of the buildings and the distances between them were transformed to full numbers and modified nominally to create the same site coverage for both typologies. They were then used as the basis for the generation of two archetypical models (i.e., one for linear and one for point buildings) of nine buildings placed on a plot with the same site coverage (Figure 5).

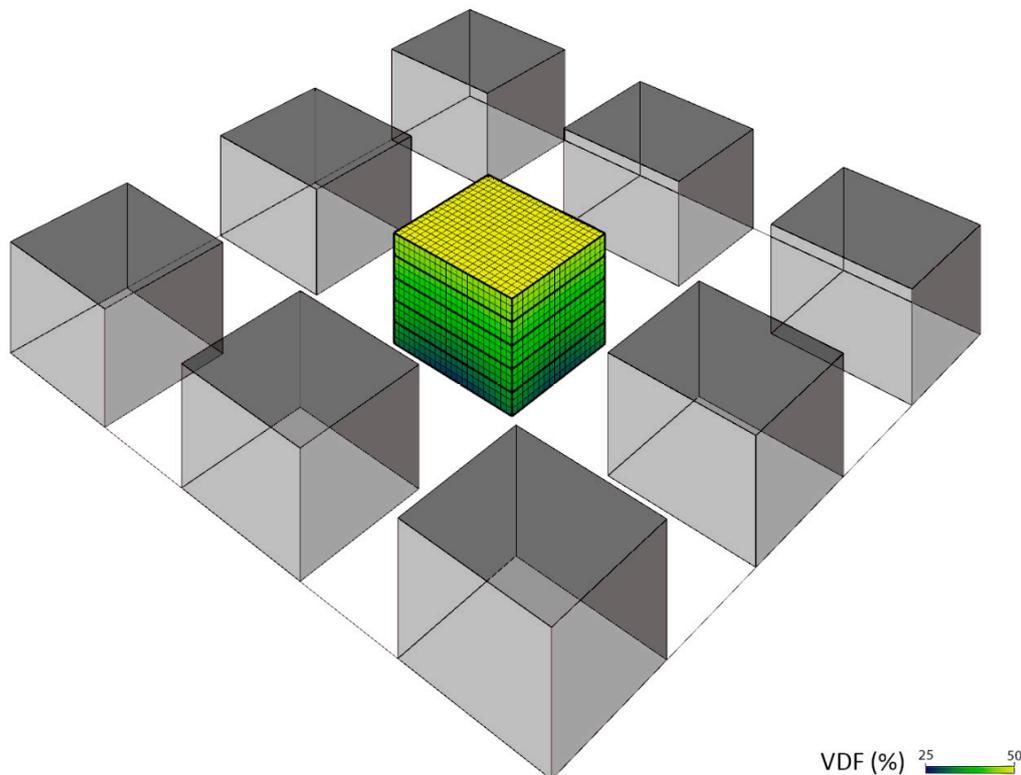
<b>site coverage</b>	<b>0.31</b>					
building typology	point buildings			linear buildings		
distance between buildings (m)	24			30		
development layout	<b>P1A</b> (parallel)	<b>P1B</b> (shifted vertically)	<b>P1C</b> (shifted horizontally)	<b>L1A</b> (parallel)	<b>L1B</b> (shifted vertically)	<b>L1C</b> (shifted horizontally)
<b>site coverage</b>	<b>0.36</b>					
building typology	point buildings			linear buildings		
distance between buildings (m)	20			25		
development layout	<b>P2A</b> (parallel)	<b>P2B</b> (shifted vertically)	<b>P2C</b> (shifted horizontally)	<b>L2A</b> (parallel)	<b>L2B</b> (shifted vertically)	<b>L2C</b> (shifted horizontally)
<b>site coverage</b>	<b>0.42</b>					
building typology	point buildings			linear buildings		
distance between buildings (m)	16			20		
development layout	<b>P3A</b> (parallel)	<b>P3B</b> (shifted vertically)	<b>P3C</b> (shifted horizontally)	<b>L3A</b> (parallel)	<b>L3B</b> (shifted vertically)	<b>L3C</b> (shifted horizontally)
<b>site coverage</b>	<b>0.50</b>					
building typology	point buildings			linear buildings		
distance between buildings (m)	12			15		
development layout	<b>P4A</b> (parallel)	<b>P4B</b> (shifted vertically)	<b>P4C</b> (shifted horizontally)	<b>L4A</b> (parallel)	<b>L4B</b> (shifted vertically)	<b>L4C</b> (shifted horizontally)
<b>site coverage</b>	<b>0.62</b>					
building typology	point buildings			linear buildings		
distance between buildings (m)	8			10		
development layout	<b>P5A</b> (parallel)	<b>P5B</b> (shifted vertically)	<b>P5C</b> (shifted horizontally)	<b>L5A</b> (parallel)	<b>L5B</b> (shifted vertically)	<b>L5C</b> (shifted horizontally)

Figure 5. Archetypical residential development model variations.

In archetypical models, point buildings with the dimensions of 22 × 18 m were placed parallel at a distance of 24 m on a plot to result in the site coverage of 0.31, with the plot boundary encompassing

the corners of the outermost buildings. Correspondingly, linear buildings with the dimensions of  $16 \times 45$  m ( $w \times l$ ) were placed on a plot at a distance of 30 m to create the site coverage of 0.31. Two further models were derived by shifting buildings vertically (along the longer side of the building) and horizontally (along the shorter side of the building) to create two variations of a chessboard pattern for the evaluation of different geometric correlations between individual buildings (Figure 5). Subsequently, the resulting six residential development patterns were densified by narrowing the space between the buildings. Specifically, this means that the distances between point buildings were changed from 24 m to 20, 16, 12 and 8 m, while in the case of linear buildings the distance between them was reduced from 30 m to 25, 20, 15 and 10 m. Such densification resulted in plots with site coverages of 0.31, 0.36, 0.42, 0.50 and 0.62, as shown in Figure 5. Floor to area ratio (FAR) and building height to building distance (H/D) ratios were calculated for heights of buildings ranging from 3 to 8 stories, with the story height approximated to 3 m. The resulting 180 variations were used to study the correlation between the requirements for daylighting expressed through minimum acceptable facade  $VDF_{avg}$ , urban density and residential development typology and placement of buildings. Each individual variation was identified by an unambiguous code (e.g., P1A) and stated FAR value (Figure 5). The first letter designates the shape of the building (i.e., L—linear, P—point), the number defines the site coverage (i.e., 1—site coverage of 0.31, 2—site coverage of 0.36, etc.), while the last letter describes the shape of the urban pattern (i.e., A—parallel, B—shifted vertically and C—shifted horizontally).

For the simulations of  $VDF_{avg}$  on the building envelope, the facades of the central building of the models (worst case scenario) were divided into story-high segments (3.00 m), upon which a grid with cells of  $1.00$  m  $\times$   $1.00$  m in size was placed (Figure 6).  $VDF$  for each of the intersection points was simulated, resulting in the determination of  $VDF_{avg}$  for each individual story.



**Figure 6.** Illustration of the simulation of  $VDF_{avg}$  on the facade of the central building of the model (variation P3A with 5 story's).

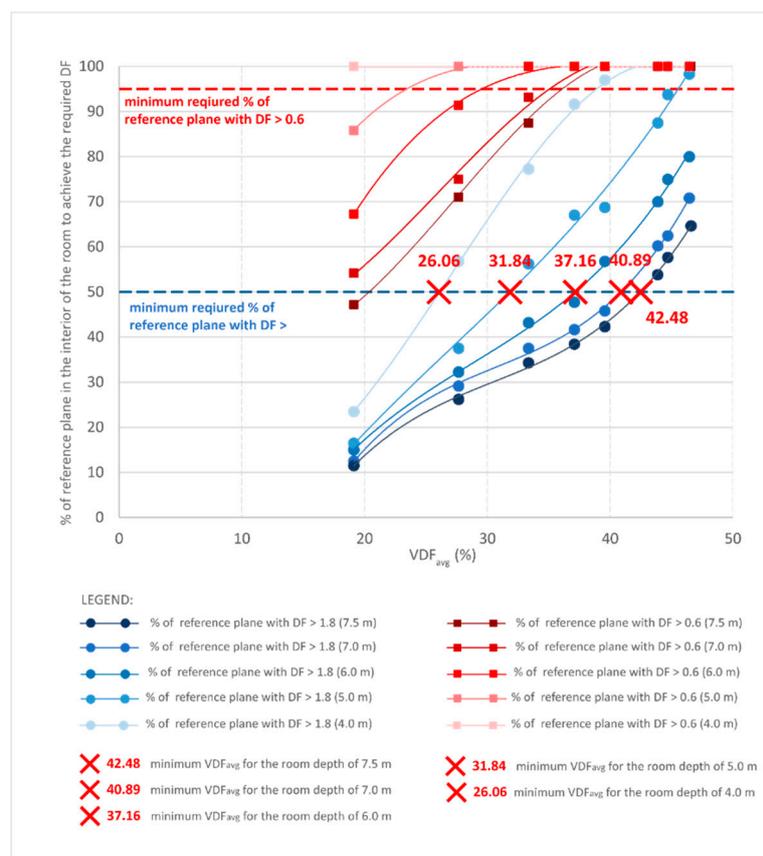
### 2.3. Step 3: Defining the Correlation between DF in the Room and Urban Planning Parameters

Finally, the maximum density in the form of a maximum floor area ratio necessary to fulfil the stipulations of EN 17037 for the deepest room permissible according to Slovenian legislation was established for the worst- and best-case layouts identified with the procedure in Section 2.2. The maximum FAR values were calculated using the polynomial trendlines ( $R^2 > 0.99$ ) connecting the values of  $VDF_{avg}$  achieved on the ground floor facade to the development FAR. These values were then compared to the determined minimum average VDF achieved in case of the tested room corresponding to the daylight requirements of EN 17037 at different depths of the room in Step 1. Finally, the maximum number of story's was deduced from the calculated development FAR and site coverage and used to recalculate threshold FARs that still allow for adequate daylighting of rooms.

## 3. Results

### 3.1. Threshold Values of $VDF_{avg}$ on the Facade for the Interior of the Room to be Lit according to EN 17037

The results of the analysis of daylight provision in rooms in Step 1 show that relatively light shading of the analyzed facade, achieved by the addition of an opposing building to the model of the room (Figure 2), reduces the amount of daylight on the indoor reference plane to the level where it no longer complies with the EN 17037 stipulations. The comparison of the fulfilment of two alternative criteria, namely the first one where a room is adequately daylight if  $DF > 1.8\%$  is achieved across 50% of the reference plane and the second one, requiring that  $DF > 0.6\%$  is achieved across 95% the reference plane in the room, shows that the first one is harder to fulfil (Figure 7).



**Figure 7.** Average vertical daylight factor ( $VDF_{avg}$ ) vs. the percentage of the reference plane in the room with the minimum achieved daylight factor (DF) according to EN 17037. The X marks denote the threshold values of  $VDF_{avg}$  for the fulfilment of the  $DF > 1.8\%$  at more than 50% of data point criteria.

Therefore, the  $VDF_{avg}$  values on the facade grid corresponding to the fulfilment of the criteria of  $DF > 1.8\%$  across more than 50% of the interior reference plane were set as threshold values for further examination of the correlation between the daylight potential of the test building and the studied residential development formation parameters. The defined  $VDF_{avg}$  thresholds were calculated from the polynomial trendlines ( $R^2 > 0.99$ ) connecting the values of  $VDF_{avg}$  on the facade of the building with the percentage of the grid points on the reference plane exceeding  $DF$  of 1.8% at different room depths. The exact values show that for the fulfilment of the stated criteria for 7.5, 7.0, 6.0, 5.0 and 4.0 m room depths with the corresponding WFRs of 20.00%, 21.43%, 25.00%, 30.00% and 37.50%, the minimum necessary values for  $VDF_{avg}$  are 42.48%, 40.89%, 37.16%, 31.84% and 26.06%, respectively (Figure 7). Specifically, this means that a facade  $VDF_{avg}$  of 42.48% (3.97 percentage point reduction in  $VDF_{avg}$  compared to the unshaded facade) already results in inadequate daylight provision in the instance of the 7.5 m deep room. Correspondingly, the value of the required minimum  $VDF_{avg}$  on the facade declines with the decrease in the depth of the room and reaches 53.90% of the unshaded facade's  $VDF_{avg}$  value ( $VDF_{avg}$  of 25.04% compared to 46.45% of the unshaded facade) in case of a 4.0 m deep room.

### 3.2. The Correlation between $VDF_{avg}$ on the Facade and Urban Planning Parameters

The examination of the  $VDF_{avg}$ s of individual story's in the case of five different ground coverage ratios, six different building heights, two building typologies and three types of building placements (Step 2 of the implemented methodology) shows an expected increase in the value of  $VDF_{avg}$  with respect to the vertical position of the story. Figure 8 demonstrates the relation between the studied urban planning parameters for each individual story in an example of two extremes (i.e., best- and worst-case variations). These are the L1B (i.e., linear buildings, site coverage of 0.31, vertically shifted rows and maximum FAR of 2.48) and the P5A (i.e., point buildings, site coverage of 0.62, parallel placement and maximum FAR of 4.96) cases. The difference between  $VDF_{avg}$  on lower story's compared to higher story's is larger for the P5A case with higher site coverage. In fact,  $VDF_{avg}$  for the 7th floor is 4.3 times higher than  $VDF_{avg}$  for the ground floor (i.e., 40.39% compared to 9.41%). Figure 8 also clearly illustrates the decrease of  $VDF_{avg}$  on the facade of the same story with the increase of building height/FAR by a maximum of 37%. Specifically, in the case of the 2nd floor of the P5A variation,  $VDF_{avg}$  is 41.05% for the FAR value of 2.48, while  $VDF_{avg}$  is 15.08% for the FAR value of 4.96. The difference between  $VDF_{avg}$  of the lower and higher site coverage variations at the same FAR is the greatest for lower story's and decreases at the upper ones. Figure 8 shows the same  $VDF_{avg}$  value on the 3rd floor at FAR 2.48 for both site coverages.

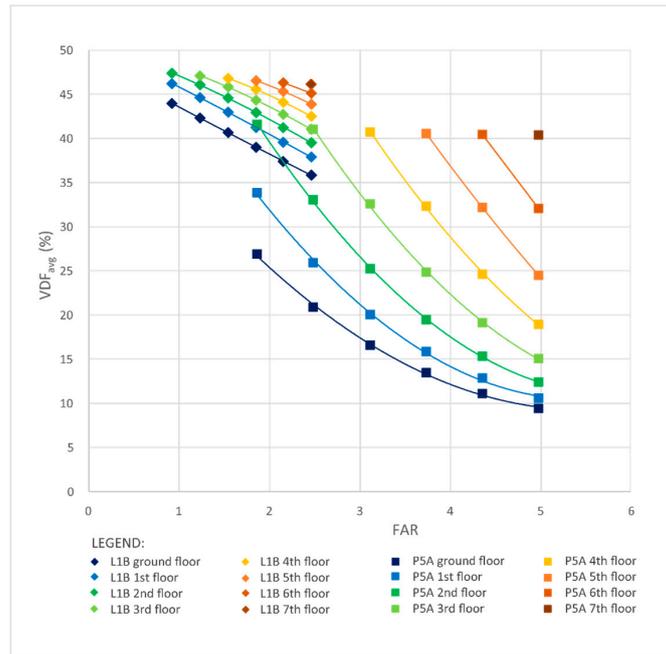


Figure 8. VDF<sub>avg</sub> on facade for different story’s and FARs for the L1B and P5A cases.

Since the ground floor represents the worst-case scenario in terms of daylighting, average vertical daylight factors on the ground floor facade for different placements and heights of point and linear buildings with different site coverage values were subsequently compared. The results of the simulations of VDF<sub>avg</sub> on the ground floor facades are summarized in Table A3 in the Appendix A. The analysis (Figure 9) shows that VDF<sub>avg</sub> on the ground floor facade decreases with the increase of FAR, showing a strong negative correlation, with the Pearson Correlation ranging from  $-1.00$  for variations with lower site coverage to  $-0.98$  for variations with higher site coverage.

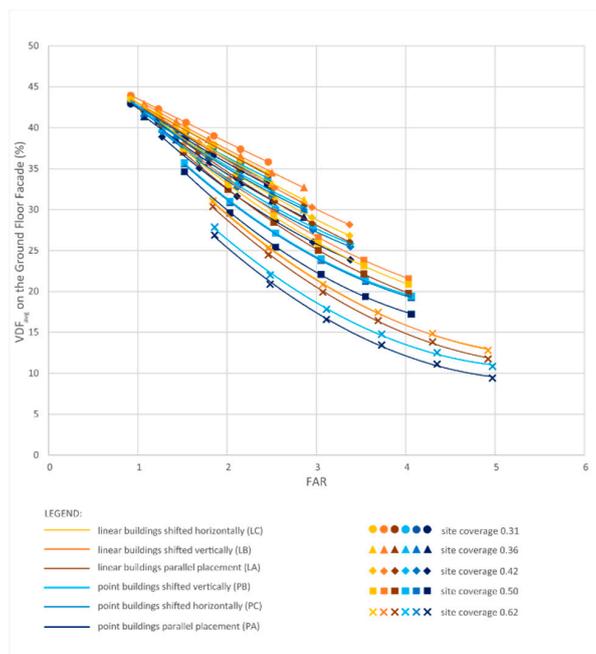
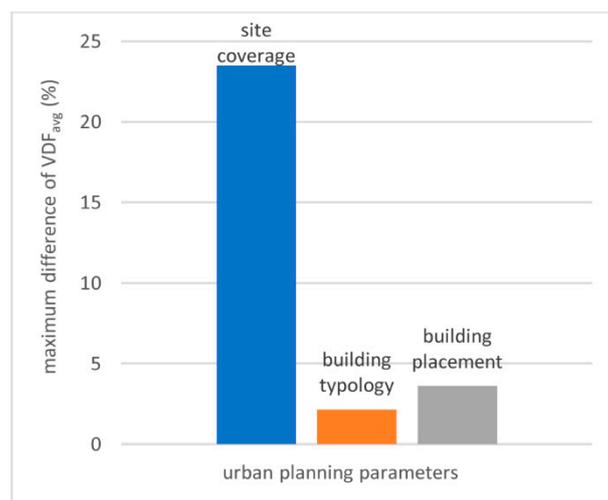


Figure 9. VDF<sub>avg</sub> trendlines for the ground floor facade of all placement variations and site coverages at different FAR values.

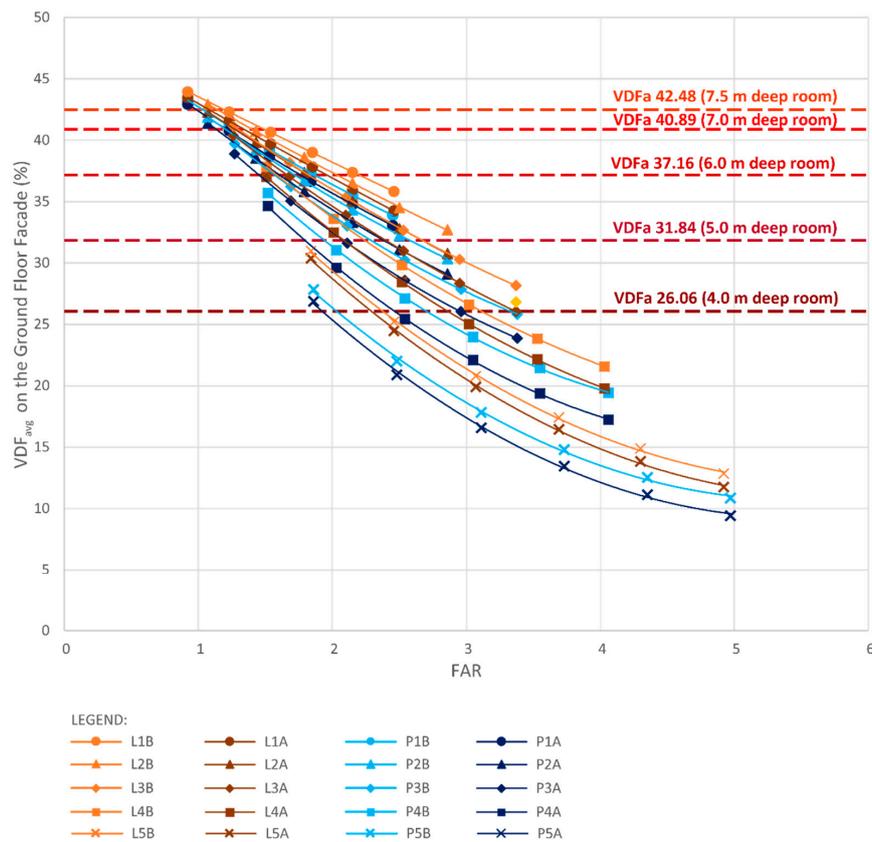
Regarding the site coverage, Figure 9 illustrates that at the same floor area ratio, site coverage values contribute significantly to the values of the achieved  $VDF_{avg}$  on the considered story's facade. In particular, at the FAR value of 2.48, which is the highest value for the site coverage of 0.31 and therefore the highest common FAR for all variations, the maximum difference between  $VDF_{avg}$  values for the same typology and placement at different site coverages is 23.50%, between P1A and P5A. At equal FAR and site coverage values, the chosen typology and placement of buildings are also a determining factor influencing the achieved average VDF. As illustrated in Figure 9, the results consistently show higher  $VDF_{avg}$  values for linear buildings for all site coverage values, the highest for the vertically shifted chessboard placement, and the lowest for the parallel placement of point buildings. The largest difference in  $VDF_{avg}$  on the ground floor facade for point buildings is 2.16% between P4A and P4B at FAR 4.00, while the largest difference for linear buildings is 2.10% between L3B and L3A at FAR 3.36. At the same site coverage, FAR and placement of the models, the maximum difference in the  $VDF_{avg}$  value on the ground floor facade is 3.61% between variations P5A and L5A. On the whole, the largest difference between the two typologies and different placements with the same site coverage and FAR values is 4.47% in the case of the P4A and L4B variations with the site coverage of 0.50 and FAR of 3.00. Compared to site coverage at the same FAR, building typology and their placement only have a moderate effect on the  $VDF_{avg}$  on the ground floor facades (Figure 10).



**Figure 10.** Impact of studied urban planning parameters on  $VDF_{avg}$  on the ground floor facades.

### 3.3. Guidelines for the Determination of Maximum Allowable Urban Densities at an Early Planning Stage

The results of the procedure for the determination of maximum FAR values of worst- and best-case layouts (described in Section 2.3) are illustrated in Figure 11 and listed in Table 2.



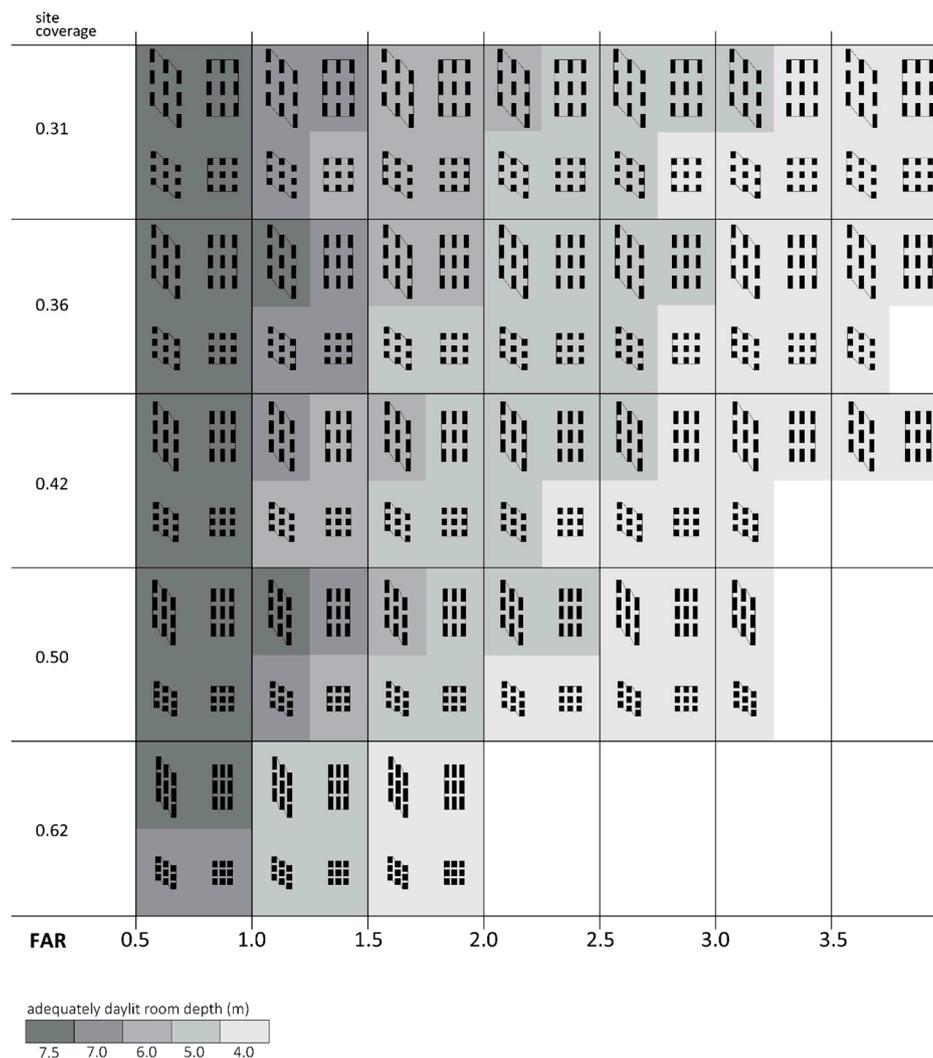
**Figure 11.** VDF<sub>avg</sub> trendlines for the ground floor facade of worst and optimum placement variations at all site coverages and different FAR values compared to the min. VDF<sub>avg</sub> to comply with EN 17037 stipulations for different depths of the room.

**Table 2.** Maximum FAR for linear and point buildings with optimal layouts and different site coverages for adequate natural lighting of different room depths according to EN 17037.

POINT BUILDINGS	Maximum FAR at Room Depth				
	7.5 m	7 m	6 m	5 m	4 m
P1A/site coverage 0.31	0.93	0.93	1.55	2.48	3.72
P1B/site coverage 0.31	0.93	1.24	1.86	2.79	4.03
P2A/site coverage 0.36	0.72	1.08	1.44	2.16	3.24
P2B/site coverage 0.36	0.72	1.08	1.44	2.52	3.60
P3A/site coverage 0.42	0.84	0.84	1.26	1.68	2.94
P3B/site coverage 0.42	0.84	0.84	1.26	2.10	2.94
P4A/site coverage 0.50	0.50	0.50	1.00	1.50	2.00
P4B/site coverage 0.50	0.50	0.50	1.00	1.50	2.00
P4B/site coverage 0.50	0.50	1.00	1.00	1.50	2.50
P5A/site coverage 0.62	-	0.62	0.62	1.24	1.86
P5B/site coverage 0.62	-	0.62	0.62	1.24	1.86
<b>LINEAR BUILDINGS</b>					
L1A/site coverage 0.31	0.93	1.24	1.86	2.79	4.03
L1B/site coverage 0.31	0.93	1.24	2.17	3.10	4.34
L2A/site coverage 0.36	0.72	1.08	1.80	2.52	3.60
L2B/site coverage 0.36	1.08	1.08	1.80	2.88	3.96
L3A/site coverage 0.42	0.84	0.84	1.26	2.10	3.36
L3B/site coverage 0.42	0.84	1.26	1.68	2.52	3.78
L4A/ site coverage 0.50	0.50	1.00	1.00	2.00	2.50
L4B/site coverage 0.50	1.00	1.00	1.50	2.00	3.00
L5A/site coverage 0.62	0.62	0.62	0.62	1.24	1.86
L5B/site coverage 0.62	0.62	0.62	0.62	1.24	1.86

The analysis shows that a relatively low maximum FAR of 0.93 is necessary to fulfil the EN 17037 requirements for the deepest room (i.e., 7.5 m) at the lowest ground coverage of 0.31. The maximum allowable FAR decreases with the increase of site coverage, the minimum being 0.62 for linear buildings at the site coverage of 0.62, and 0.50 for point buildings at the site coverage of 0.5 (Table 2). When the depth of the room required to be lit according to EN 17037 is decreased to 4.0 m, the maximum FAR reaches the value of 4.34 for linear and 4.03 for point buildings at the site coverage of 0.31.

The findings of the final analysis of the two optimum placements of point and linear buildings are summarized in a diagram (Figure 12), where the relationship of the floor area ratio, site coverage and typology of the residential development with respect to the successfully daylit room depth of the room on the ground floor of the building is depicted.



**Figure 12.** Adequately daylit room depth of a room, placed on the ground floor of the building with respect to FAR, site coverage and typology of the development for optimum and worst variation placements of point and linear buildings.

## 4. Discussion

### 4.1. Novelty and Restrictions of the Suggested Methodological Approach

In the current study, floor area ratio and site coverage are used as indicators of density, as opposed to the building height to building distance ratio, employed in studies of urban canyons [27,29,30]. Since maximum FAR and site coverage are commonly used for density restrictions in urban zoning

plans, while at the same time they can be universally applied to any building typology and urban morphology, their direct connection to indoor daylight potential would prove useful in the early planning stages of new residential developments. In this way, the values of maximum permissible FAR and site coverage defined according to the achieved indoor daylight values would connect the decision taken on the level of urban planning to the indoor environmental conditions of the building. Thus, the sustainability issues of residential developments are addressed by optimizing the contradicting design criteria of adequate daylighting (i.e., an element of social and economic sustainability) and sustainable urban land use (i.e., an element of economic and environmental sustainability), with the aim to find the design with the highest urban density that still allows for adequately daylit indoor spaces. This does not mean that high densities are preferable. On the contrary, the proposed methodology and results could serve to prevent developers and urban planners from excessive densification of urban plans. Furthermore, FAR and site coverage values can be easily altered by an amorphous/irregular building plot boundary and the setback of the buildings from the plot boundary. In the models used, the plot boundary encompasses the corners of the outermost buildings without adding any additional area of the plot that would be created by the setback, which means that the  $VDF_{avg}$  values calculated are higher than they would be with the setback or irregular boundary with the same FAR. The findings of the study should therefore be used by taking this into account (e.g., by drawing an additional boundary around the planned/real life buildings edges). Additionally, the distribution of buildings and building heights in residential developments is usually not as uniform as in the models used in the study. However, the distribution of buildings in the developments Brdo and Polje, used for the generation of archetypical models analyzed, shows a marked effort by the planners to create equal conditions by arranging the buildings as evenly as possible. In the mentioned real-life cases, the vertical variation of buildings is in the range of maximum one story, making them comparable to the models.

#### *4.2. Implications of the Results for Urban Planning Parameters in the Slovenian Context*

Regardless of the above-stated discrepancies between idealized models and the real-life cases, the methodological approach used in the present study proved to be applicable in defining urban planning constraints, using standardized metrics in order to provide conditions for adequate daylighting in the earliest design stages of residential developments.

The maximum calculated residential development FAR for the deepest allowable rooms on the ground floor of the building, designed according to Slovenian legislation, to be daylit in conformance to EN 17037, is 0.93. This value is in some cases lower than the actual FARs of recent real-life developments, analyzed in this study. The findings suggest that in the instance where indoor spaces were designed according to the minimum national legislative requirements, they would not be deemed as sufficiently daylit in accordance with the EN 17037 requirements. Additionally, the buildings in the developments Polje and Brdo are set back from the building plot boundary, which would suggest even lower  $VDF_{avg}$  values at the same FAR value, in comparison to the models. This, however, does not signify that the rooms in the studied developments are not successfully daylit, as the relationship of the building form with indoor illumination is not as straightforward as it is with received solar irradiation on the external facades and with the energy potential of a building [48]. Urban indicators are inadequate for a complete daylight prediction, since individual characteristics that pertain to interior layout (e.g., room distribution, room depths, etc.) have a strong impact on the amount of daylight in the interior [37]. However, the present research does give some insight into the connection between them, showing that maximum allowable room depths according to Slovenian legislation are not applicable at higher densities, and it indicates the possibilities of optimizing the urban layout in terms of daylight availability.

FAR and site coverage (at the same FAR) were found to be the most influential of the four investigated urban planning parameters. Both parameters were identified as influential in previous studies on solar potential of urban developments [23,24]. Therefore, our findings are not surprising. The novelty of this research is the extent of the impact of typology and placement of buildings at the

same site coverage on the daylight reaching the building facade. Lower acceptable FARs in the case of point building typology were expected, as the building footprints are more dispersed than in the case of linear buildings and are, therefore, placed at smaller distances from one-another. This, however, should not directly lead to the conclusion that linear building typology is preferable in comparison to point buildings. Importantly, the latter typology has a larger share of rooms that can be placed in the corners of a building (not considered in the present study), enabling a two-sided placement of windows and therefore at least theoretically better indoor daylighting conditions.

The effect of shifting the placement of buildings in the urban layout on the resulting  $VDF_{avg}$  on the facades is proven to be positive. The influence is stronger in the point building typology, which can again be attributed to its more dispersed footprints and, therefore, higher effect of shifting the buildings in relation to the neighboring ones on the consequential  $VDF_{avg}$ . Shifting along the longer side of the building, thus exposing a greater portion of the facade to daylight, has a stronger influence than shifting along the shorter side. The distinction is stronger with linear buildings, where the ratio of the length to the width of the building is higher.

#### 4.3. General Applicability of the Presented Methodological Approach

Although the use of a specific weather file (i.e., location) and the Slovenian legislation about WFR and the geometry of a room make the results of the presented study specific in the Slovenian context, the presented methodological approach could be easily applied in other countries. This is particularly true for the EU member states, where the recommendations of EN 17037 should be considered and similar legislative guidelines and/or recommendations regarding minimal WFRs [49] and room geometries (e.g., [50]) are in force. In countries outside of EU, other recommendations about minimal daylighting in buildings, WFRs and room geometry [51] could be used to correlate the amount of daylight on the facade with the appropriate daylighting of a room. Dividing the methodology into three steps enables a flexible use of the results of each step. The geometric properties of the room in Step 1 can be altered to fit other national legislations/minimum requirements about WFR and room size, whereas the weather file and the properties of residential development models in Step 2 can be changed to fit other climactic conditions and residential typologies, with the resulting connection of the two in Step 3 being amended accordingly. Despite the fact that the actual threshold density values for other countries would differ from those obtained for Slovenia, some general conclusions about the influence of certain urban planning parameters on the daylighting of rooms can be drawn.

In terms of density, the results of the presented research show that either higher WFRs, shallower rooms or relatively low densities of residential developments are required to achieve sufficiently daylit rooms. Since 20% minimum WFR prescribed in Slovenia is already among the highest in the European Union [49] (e.g., 10% for Sweden and Denmark; 12.5% for Poland, Italy and Germany; and 17% for France), the findings seem to suggest that relatively low site coverage values and FAR ratios would be necessary to fulfil the requirements of the EN 17037 standard. This means that even though the general consensus supports urban density as a sustainability principle [5], the appropriate urban form and density are dependent upon the specific sustainability goals we are targeting. Since adequate daylight provision is only one of the aspects to be examined when debating sustainable cities, it needs to be assessed in the wider context of other sustainability goals (e.g., rational land use, access to open spaces and views etc.). Therefore, the findings of the study and their implications about the urban planning parameters of residential developments should be regarded in a broader context of social, environmental and economic sustainability, and evaluated with regard to other aspects of urban planning.

## 5. Conclusions

In this research, 180 variations of archetypal residential development models were examined to investigate the impact of urban planning parameters on the daylighting potential of buildings. A methodological approach was developed to link site coverage, floor area ratio, building typology and

placement to the daylighting of a typical room, defined by specific legislative restrictions about its geometry and minimum required window to floor area ratio. The impact of the examined urban planning parameters on the daylighting potential proved to be considerable, with a strong negative correlation between the average vertical daylight factor and the floor area ratio. The main findings of the research are:

- Site coverage at the same floor area ratio has a significant impact on the average vertical daylight factor on the facade, which increases with the rise of the floor area ratio value, while the building typology and placement of buildings are identified as having a moderate impact. Facades of linear buildings exhibit a higher average vertical daylight factor compared to those of point buildings at the same site coverage and floor area ratio, while parallel placement of buildings causes a lower average vertical daylight factor compared to a shifted (chessboard) pattern;
- If the rooms are designed according to minimum Slovenian standards, a relatively low FAR of 0.93 for residential developments is necessary to fulfil the requirements for minimum daylight provision according to EN 17037. At higher densities, shallower rooms with higher WFRs are to be considered. The summary of the research results (Figure 12), conceived as a guideline for the architects and planners, shows the relationship between room depth, FAR, site coverage and the placement of buildings. By utilizing it, the development densities, building typology, placement of buildings and room depth can be adjusted in the early design stages of the projects in order to enable sufficiently daylit rooms;
- The three-step approach, used in this study, is universal and can be applied in countries other than Slovenia. With the use of other national legislations/minimum requirements about WFR and room size and taking different climactic conditions into account, other national urban planning guidelines with the aim to optimize the urban plan in terms of daylight could be formed.

The presented methodological approach and findings fill a gap between the urban planning parameters and the indoor conditions (specifically daylighting) of buildings by simultaneously addressing two aspects of the built environment sustainability issues—the sustainable urban land use and the quality of indoor environment. Therefore, the proposed methodological approach strengthens the connection between architectural and urban design by addressing the issue of daylighting at the urban scale. In this manner, the synergetic potential for the increase of the quality and sustainability of the built environment is not neglected, as is the norm in the conventional design process. Future work in relation to the presented approach and results should focus on the investigation of correlating the urban daylighting criteria with the received solar irradiation on the building envelope, its potential energy performance and an estimation of the views out of the room. Thus, urban planning guidelines based on multiple parameters, geared towards higher urban and overall sustainability of built environment, would be given.

**Author Contributions:** All authors have read and agree to the published version of the manuscript. Conceptualization, N.Š. and M.K.; methodology, N.Š. and M.K.; investigation, N.Š.; visualization, N.Š.; writing—original draft preparation, N.Š.; writing—review and editing, M.K. All authors have read and agreed to the published version of the manuscript.

**Funding:** This article is a result of a doctoral research by the first author (N.Š.), which was in part financed by the European Union, European Social Fund and the Republic of Slovenia, Ministry for Education, Science and Sport in the framework of the Operational program for human resources development. The second author (M.K.) acknowledges the financial support from the Slovenian Research Agency (research core funding No. P2 – 0158).

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

## Appendix A

**Table A1.** The main characteristics of the linear building residential development Brdo.

Name/Project Phase	No. of Bldg	No. of Story's	Length [m]	Width [m]	Min. Dist. [m]	Max. Dist. [m]	Place-ment	Site Cover-Age	FAR
BRDO F4	1	6	30.10	15.70	15.02	44.00	parallel with rotation	0.25	1.32
	2	5	40.90	15.70					
	1	5	61.80	15.70					
	1	6	61.80	15.70					
BRDO F5	2	5	28.70	15.20	21.73	22.90	chess-board pattern	0.23	1.14
	1	6	28.70	15.20					
	1	5	40.60	15.20					
	2	5	51.70	15.20					
	2	6	51.70	15.20					
average		5.44	44.00	15.42	18.38	33.45		0.24	1.23

**Table A2.** The main characteristics of the linear building residential development Polje.

Name/Project Phase	No. of Bldg	No. of Story's	Length [m]	Width [m]	Min. Dist. [m]	Max. Dist. [m]	Place-ment	Site Cover-Age	FAR
POLJE I	6	4	21.00	14.70	14.20	21.17	parallel	0.17	0.69
POLJE II	6	4	26.60	26.60	7.90	34.48	chess-board pattern	0.30	1.13
POLJE III	2	4	28.50	22.90	10.80	19.64	chess-board pattern	0.28	1.13
	2	4	21.02	18.76					
	2	4	18.76	11.48					
average		4.00	23.18	18.89	10.97	25.10		0.25	0.98

**Table A3.**  $VDF_{avg}$  on the ground floor facades of all variations of archetypical residential development models.

No. of Story's	FAR	$VDF_{avg}$ on the Ground Floor Facades [%]						
		Point Buildings			Linear Buildings			
site coverage 0.31								
		P1A	P1B	P1C	L1A	L1B	L1C	
3	0.93	42.92	43.23	43.10	43.46	43.94	43.51	
4	1.24	40.78	41.23	41.06	41.59	42.31	41.65	
5	1.55	38.67	39.23	38.99	39.69	40.65	39.78	
6	1.86	36.65	37.32	37.03	37.81	39.00	37.92	
7	2.17	34.78	35.53	35.20	36.00	37.40	36.12	
8	2.48	33.07	33.90	33.53	34.29	35.86	34.42	
site coverage 0.36								
		P2A	P2B	P2C	L2A	L2B	L2C	
3	1.08	41.39	41.87	41.75	42.28	42.91	42.40	
4	1.44	38.55	39.24	39.06	39.83	40.76	40.01	
5	1.80	35.84	36.72	36.48	37.39	38.61	37.62	
6	2.16	33.35	34.37	34.11	35.04	36.52	35.33	
7	2.52	31.12	32.26	31.97	32.84	34.55	33.18	
8	2.88	29.16	30.40	30.09	30.82	32.73	31.21	

Table A3. Cont.

No. of Story's	FAR	VDF <sub>avg</sub> on the Ground Floor Facades [%]					
		Point Buildings			Linear Buildings		
site coverage 0.42							
		P3A	P3B	P3C	L3A	L3B	L3C
3	1.26	38.90	39.71	39.53	40.38	41.15	40.62
4	1.68	35.10	36.23	35.98	37.08	38.19	37.43
5	2.10	31.65	33.05	32.75	33.92	35.34	34.37
6	2.52	28.66	30.27	29.93	31.01	32.70	31.56
7	2.94	26.11	27.89	27.53	28.41	30.32	29.05
8	3.36	23.99	25.88	25.51	26.12	28.22	26.85
site coverage 0.5							
		P4A	P4B	P4C	L4A	L4B	L4C
3	1.50	34.67	35.74	35.59	37.03	37.84	37.44
4	2.00	29.65	31.07	30.88	32.51	33.65	33.10
5	2.50	25.50	27.17	26.97	28.51	29.88	29.24
6	3.00	22.18	24.03	23.82	25.10	26.65	25.95
7	3.50	19.51	21.52	21.32	22.24	23.92	23.21
8	4.00	17.35	19.51	19.31	19.86	21.65	20.95
site coverage 0.61							
		P5A	P5B	P5C	L5A	L5B	L5C
3	1.86	26.93	27.94	27.92	30.43	31.15	31.02
4	2.48	20.93	22.10	22.09	24.53	25.41	25.28
5	3.10	16.64	17.92	17.91	20.01	20.96	20.86
6	3.72	13.56	14.89	14.91	16.59	17.57	17.53
7	4.34	11.28	12.67	12.71	13.98	14.97	14.99
8	4.96	9.58	11.02	11.08	11.97	12.96	13.04
3	1.86	26.93	27.94	27.92	30.43	31.15	31.02

## References

- Mori, K.; Fujii, T.; Yamashita, T.; Mimura, Y.; Uchiyama, Y.; Hayashi, K. Visualization of a City Sustainability Index (CSI): Towards transdisciplinary approaches involving multiple stakeholders. *Sustainability* **2015**, *7*, 12402–12424. [CrossRef]
- Jabareen, Y.R. Sustainable urban forms: Their typologies, models, and concepts. *J. Plan. Educ. Res.* **2006**, *26*, 38–52. [CrossRef]
- European Commission, Directorate General for Regional Policy. *Cities of Tomorrow—Challenges, Visions, Ways Forward*; European Union: Luxembourg, 2011. [CrossRef]
- Yi, Y.; Ma, S.; Guan, W.; Li, K. An empirical study on the relationship between urban spatial form and CO<sub>2</sub> in Chinese cities. *Sustainability* **2017**, *9*, 672. [CrossRef]
- Ahmadian, E.; Sodagar, B.; Mills, G.; Byrd, H.; Bingham, C.; Zolotas, A. Sustainable cities: The relationships between urban built forms and density indicators. *Cities* **2019**, *95*, 102382. [CrossRef]
- Bramley, G.; Power, S. Urban form and social sustainability: The role of density and housing type. *Environ. Plan. B Plan. Des.* **2009**, *36*, 30–48. [CrossRef]
- Boubekri, M. *Daylighting, Architecture and Health: Building Design Strategies*, 1st ed.; Elsevier/Architectural Press: Amsterdam, The Netherlands, 2008; p. 418.
- Brown, M.J.; Jacobs, D.E. Residential Light and Risk for Depression and Falls: Results from the LARES Study of Eight European Cities. *Public Health Rep.* **2017**, *126*, 131–140. [CrossRef] [PubMed]
- Rahman, S.A.; Hilaire, M.A.S.; Lockley, S.W. The effects of spectral tuning of evening ambient light on melatonin suppression, alertness and sleep. *Physiol. Behav.* **2017**, *177*, 221–229. [CrossRef]
- Davis, S.; Kaune, W.T.; Mirick, D.K.; Chen, C.; Stevens, R.G. Residential magnetic fields, light-at-night, and nocturnal urinary 6-sulfatoxymelatonin concentration in women. *Am. J. Epidemiol.* **2001**, *154*, 591–600. [CrossRef]

11. Boubekri, M.; Cheung, I.N.; Reid, K.J.; Wang, C.H.; Zee, P.C. Impact of Windows and Daylight Exposure on Overall Health and Sleep Quality of Office Workers. *J. Clin. Sleep Med.* **2014**, *10*, 603–611. [[CrossRef](#)]
12. Berson, D.M.; Dunn, F.A.; Takao, M. Phototransduction by Retinal Ganglion Cells That Set the Circadian Clock. *Science* **2002**, *295*, 1070–1073. [[CrossRef](#)]
13. Andersen, M.; Gochenour, S.J.; Lockley, S.W. Modelling “non-visual” effects of daylighting in a residential environment. *Build. Environ.* **2013**, *70*, 138–149. [[CrossRef](#)]
14. Li, D.H.W. A review of daylight illuminance determinations and energy implications. *Appl. Energy* **2010**, *87*, 2109–2118. [[CrossRef](#)]
15. Yu, X.; Su, Y. Daylight availability assessment and its potential energy saving estimation—A literature review. *Renew. Sustain. Energy Rev.* **2015**, *52*, 494–503. [[CrossRef](#)]
16. Herczeg, M.; McKinnon, D.; Miliotis, L.; Bakas, I.; Klaassens, E.; Svatikova, K.; Widerberg, O. *Resource Efficiency in the Building Sector: Final Report*; ECORYS Nederland BV: Rotterdam, The Netherlands, 2014; p. 124.
17. Schweizer, C.; Edwards, R.D.; Bayer-Oglesby, L.; Gauderman, W.J.; Ilacqua, V.; Juhani Jantunen, M.; Lai, H.K.; Nieuwenhuijsen, M.; Künzli, N. Indoor time-microenvironment-activity patterns in seven regions of Europe. *J. Expo. Sci. Environ. Epidemiol.* **2007**, *17*, 170–181. [[CrossRef](#)] [[PubMed](#)]
18. Dovjak, M.; Kukec, A. *Creating Healthy and Sustainable Buildings*; Springer Open: Cham, Switzerland, 2019. [[CrossRef](#)]
19. Darula, S.; Christoffersen, J.; Malikova, M. Sunlight and insolation of building interiors. *Energy Procedia* **2015**, *78*, 1245–1250. [[CrossRef](#)]
20. Ministry of the Environment and Spatial Planning of the Republic of Slovenia. *TSG-1-004:2010—Efficient Use of Energy*; Ministry of the Environment and Spatial Planning of the Republic of Slovenia: Ljubljana, Slovenia, 2010.
21. Ministry of the Environment and Spatial Planning of the Republic of Slovenia. *Rules on Minimum Technical Requirements for the Construction of Apartment Buildings and Apartments*; Ministry of the Environment and Spatial Planning of the Republic of Slovenia: Ljubljana, Slovenia, 2011.
22. Slovenian Institute for Standardization. *SIST EN 17037: 2019 Daylight of Buildings*; Slovenian Institute for Standardization: Ljubljana, Slovenia, 2019.
23. Nault, E.; Peronato, G.; Rey, E.; Andersen, M. Review and critical analysis of early-design phase evaluation metrics for the solar potential of neighborhood designs. *Build. Environ.* **2015**, *92*, 679–691. [[CrossRef](#)]
24. Compagnon, R. *PRECis: Assessing the Potential for Renewable Energy in Cities—Solar and Daylight Availability in Urban Areas*; Final Technical Report; Ecole d’ingénieurs et d’architectes de Fribourg: Fribourg, Switzerland, 2000; p. 47.
25. Compagnon, R. Solar and daylight availability in the urban fabric. *Energy Build.* **2004**, *36*, 321–328. [[CrossRef](#)]
26. Natanian, J.; Auer, T. Balancing urban density, energy performance and environmental quality in the Mediterranean: A typological evaluation based on photovoltaic potential. *Energy Procedia* **2018**, *152*, 1103–1108. [[CrossRef](#)]
27. Cheng, V.; Steemers, K.; Montavon, M.; Compagnon, R. Urban Form, Density and Solar Potential. In Proceedings of the PLEA 2006 23rd International Conference on Passive and Low Energy Architecture, Geneva, Switzerland, 6–8 September 2006; pp. I701–I706.
28. Lobaccaro, G.; Carlucci, S.; Croce, S.; Paparella, R.; Finocchiaro, L. Boosting solar accessibility and potential of urban districts in the Nordic climate: A case study in Trondheim. *Sol. Energy* **2017**, *149*, 347–369. [[CrossRef](#)]
29. Košir, M.; Capeluto, I.G.; Krainer, A.; Kristl, Ž. Solar potential in existing urban layouts—Critical overview of the existing building stock in Slovenian context. *Energy Policy* **2014**, *69*, 443–456. [[CrossRef](#)]
30. Nasrollahi, N.; Shokri, E. Daylight illuminance in urban environments for visual comfort and energy performance. *Renew. Sustain. Energy Rev.* **2016**, *66*, 861–874. [[CrossRef](#)]
31. Li, D.H.W.; Cheung, G.H.W.; Cheung, K.L.; Lam, J.C. Simple method for determining daylight illuminance in a heavily obstructed environment. *Build. Environ.* **2009**, *44*, 1074–1080. [[CrossRef](#)]
32. Rohli, R.V.; Vega, A.J. *Climatology*, 4th ed.; Jones & Bartlett Learning: Burlington, NJ, USA, 2018; p. 418.
33. Iversen, A.; Nielsen, T.R.; Svendsen, S.H. Illuminance level in the urban fabric and in the room. *Indoor Built Environ.* **2011**, *20*, 456–463. [[CrossRef](#)]
34. Iversen, A. Development of a Simple Framework to Evaluate Daylight Conditions in Urban Buildings in the Early Stages of Design. Ph.D. Thesis, Technical University of Denmark, Lyngby, Denmark, 2013.

35. Strømmand-Andersen, J.; Sattrup, P.A. The urban canyon and building energy use: Urban density versus daylight and passive solar gains. *Energy Build.* **2011**, *43*, 2011–2020. [[CrossRef](#)]
36. Zhang, J.; Heng, C.K.; Malone-Lee, L.C.; Huang, Y.C.; Janssen, P.; Jun, D.; Hii, C.; Nazim, I. Preliminary Evaluation of a Daylight Performance Indicator for Urban Analysis: Facade Vertical Daylight Factor Per Unit Floor Area. In Proceedings of the Fifth National Conference of IBPSA-USA, Madison, WI, USA, 1–3 August 2012.
37. Bournas, I.; Dubois, M.C. Daylight regulation compliance of existing multi-family apartment blocks in Sweden. *Build. Environ.* **2019**, *150*, 254–265. [[CrossRef](#)]
38. De Luca, F.; Dogan, T. A novel solar envelope method based on solar ordinances for urban planning. *Build. Simul.* **2019**, *12*, 817–834. [[CrossRef](#)]
39. McNeel Robert and Associates Rhino Version 5.0 2017. Available online: <https://www.rhino3d.com/> (accessed on 30 December 2019).
40. Davidson, S. Grasshopper: Algorithmic Modelling for Rhino 2017. Available online: <https://www.grasshopper3d.com/page/download-1> (accessed on 30 December 2019).
41. Solemma LCC DIVA-for-Rhino 4.0 2019. Available online: <http://solemma.net/Diva.html> (accessed on 30 December 2019).
42. McNeil, A.; Lee, E.S. A validation of the Radiance three-phase simulation method for modelling annual daylight performance of optically complex fenestration systems. *J. Build. Perform. Simul.* **2012**, *6*, 24–37. [[CrossRef](#)]
43. U.S. Department of Energy’s Building Technologies Office EnergyPlus. Available online: <https://energyplus.net/weather-search/ljubljana> (accessed on 20 August 2018).
44. Lee, J.; Boubekri, M.; Liang, F. Impact of building design parameters on daylighting metrics using an analysis, prediction, and optimization approach based on statistical learning technique. *Sustainability* **2019**, *11*, 1474. [[CrossRef](#)]
45. Tregenza, P.; Mardaljevic, J. Daylighting buildings: Standards and the needs of the designer. *Light. Res. Technol.* **2018**, *50*, 63–79. [[CrossRef](#)]
46. Open House Slovenia: Zeleni gaj Brdo Housing. Available online: <https://www.openhouseslovenia.org/objekt/stanovanjska-soseska-zeleni-gaj-na-brdu/> (accessed on 5 August 2019).
47. Open House Slovenia: Residential Neighbourhoods Polje I, II and III. Available online: <https://www.openhouseslovenia.org/objekt/stanovanjska-soseska-polje-i-ii-in-iii/> (accessed on 5 August 2019).
48. Chatzipoulka, C.; Compagnon, R.; Nikolopoulou, M. Urban geometry and solar availability on façades and ground of real urban forms: Using London as a case study. *Sol. Energy* **2016**, *138*, 53–66. [[CrossRef](#)]
49. Kunkel, S.; Kontonasiou, E.; Acipowska, A.; Mariottini, F.; Atanasu, B. *Indoor Air Quality, Thermal Comfort and Daylight: Analysis of Residential Building Regulations in Eight EU Member States*; Buildings Performance Institute Europe: Brussels, Belgium, 2015; p. 98.
50. Ministry of the Environment, Spatial Planning and Construction of the Republic of Croatia. *Regulations on Minimum Technical Conditions for Designing and Construction of Apartments from Socially Promoted Housing Programs*; Ministry of the Environment, Spatial Planning and Construction of the Republic of Croatia: Zagreb, Croatia, 2004.
51. Foster, S.; Hooper, P.; Kleeman, A.; Martino, E.; Giles-Corti, B. The high life: A policy audit of apartment design guidelines and their potential to promote residents’ health and wellbeing. *Cities* **2020**, *96*, 102420. [[CrossRef](#)]

