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A Parametric Approach for Evaluating Solar Panel Insolation in Urban Areas: Courtyard Design Case Study

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KEYWORDS

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ABSTRACT

Stand-alone solar panel orientation (tilt and azimuth angles) for potential locations in built-up urban areas, significantly influences the level of insolation received by the panel. One way to maximize energy production involves finding the optimal orientation for each location to ensure the highest insolation for a certain number of solar panels in urban areas. The general rule used in practice is to orient the panels towards the south and calculate the horizontal tilt angle based on the latitude. However, in built-up urban areas, a more comprehensive analysis of other factors is needed, such as solar radiation levels, weather data, and shading cast by nearby buildings. In this research, a parametric approach aimed at determining the optimal orientation of stand-alone solar panels for a predefined set of potential locations is designed. Input parameters are the geometry of nearby buildings, solar panel shape, and weather data for the urban location. The approach's adaptability to different geographic locations and urban environments is achieved by adjusting input data. Comparative analysis between insolation values with the optimal orientation of solar panels and those commonly employed in practice is used for evaluation. The proposed approach is applied to determine the tilt and azimuth angles of fixed stand-alone solar panels in urban courtyards in order to improve decisions regarding the distribution of solar panels in urban planning practice. This study examines solar panel insolation in simplified geometrical representations of some urban areas with courtyards.

Introduction

The orientation and locations of solar panels is an important aspect in architectural and urban design due to their capacity to harness and convert solar energy into electrical energy (Moghadam et al., 2011; Moghadam & Deymeh, 2015; Ashetehe et al., 2022). This research focuses on the fixed stand-alone solar panels, as fixed panels have been shown to be the most cost-effective (Michaelides et al., 1999; Mousazadeh et al., 2009; Kanyarusoke et al., 2015). Many studies (Elminir et al., 2006; Berrill & Blair, 2007; Gunerhan & Hepbasli, 2007; N'Tsoukpoe, 2022; Bahrami et al., 2022) have recommended that fixed solar panels in the northern hemisphere should be oriented south-facing with the optimum tilt angle that depends on latitude.

Solar radiation is site-specific, with monthly, seasonal, and yearly variations, and the optimal orientation and location of solar panels for capturing maximum solar radiation is different in each urban location (Yadav & Chandel, 2013). Recent studies aim to enhance the location

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(Moghadam & Deymeh, 2015; Díaz-Dorado et al., 2011) or alter the tilt angle of the solar panel (Tang & Wu, 2004; Nfaoui & El-Hami, 2018; Jing et al., 2023), and some studies analyze both the tilt angle and orientation of solar panels (Kacira et al., 2004; Skeiker, 2009; Jafarkazemi & Saadabadi, 2013; Markam et al., 2016) in order to improve energy efficiency. In built-up urban areas, the complex surroundings make predicting the optimal orientation and location accurately harder, emphasizing the importance of considering all three parameters in solar simulations: location, tilt and azimuth angles.

Geometry of the built environment have impact on urban surface level of insolation (Bajšanski et al., 2019; Milošević et al., 2017). However, in dense urban areas, the built environment acts as a barrier affecting solar panel insolation, leading to a substantial reduction in a solar panel's power (Ratti et al., 2005; Vulkan et al., 2018) even a small part of it is shaded (Karatepe et al., 2008; Ibrahim, 2011; Aslani & Seipel, 2023). Studies by Xie (2023) and Zhang (2019) emphasize the significance of the built environment for solar potential, highlighting the correlation between urban morphology and the possibility of orienting and locating solar panels.

In the studies done by Moghadam and Deymeh (2015) and Siraki and Pillay (2012) impacts of shading from the built environment on the insolation level of stand-alone solar panels are considered. However, the research is confined to urban areas surrounded by two tall buildings, providing recommendations specific to these scenarios. Díaz-Dorado's (2011) study demonstrates the importance of considering shading for the best location of photovoltaic solar trackers on a building with an irregular shape. Amado and Poggi (2014) employ urban shadow simulation to quantify the solar energy potential of photovoltaic systems in the urban context, aiming to enhance city energy performance.

In this study, a parametric approach is used to determine the tilt and azimuth angles of fixed stand-alone solar panels in order to maximize the insolation of a panel. The case study demonstrate how this approach is used to optimize other courtyard elements layout. By importing urban location data, weather data, and a 3D model of the courtyards, this approach simulates insolation levels of stand-alone solar panels for predetermined urban areas in any city and urban morphology. The geometry of the courtyards, cast shadows, location data, and weather data specific to the corresponding urban location are taken into account in the simulation. The approach is applied in different courtyards, aiming to enhance decisions regarding the distribution of solar panels and other urban elements in urban planning practice.

Apart from previously mentioned research that pertains impacts of shading from the built environment on the insolation level of stand-alone solar panels, method presented in this research takes account distribution of other urban elements as a part of urban design process. Method is designed to fit the modeling workflow commonly used by urban designers. The advantage of our approach over alternative approaches (such as models that quantify the solar energy potential of photovoltaic systems) is the ability to combine 3D modelling, parametric design and environmental analysis in the same CAD environment familiar to architects and urban planners in urban planning practice. Compared to PVsyst and other similar software, the integration of Rhinoceros, Grasshopper and Ladybug, used in this study, allows application of the optimization algorithms of the other urban elements which use solar panel energy in CAD environment.

Method

In order to calculate solar panels insolation for each predetermined location in some courtyards, a parametric approach consists of following phases:

1. Import the 3D geometry of the courtyard
2. Solar panel orientation procedure
3. Solar panels insolation simulation and calculation
4. Export numerical results

The first phase is modelling geometry representing the courtyard in any 3D modelling program. The 3D model includes:

– buildings geometry that can affect the shading of the solar panel;
– a set of points representing all possible solar panel locations.

Buildings and points are fixed and can be created in or imported to Rhinoceros 3D, a computer-aided design (CAD) program, to provide a digital environment for parametric study. Buildings are modelled as non-transparent solid forms that casts full shadows. Geometric characteristics of buildings are base shape, height and façade details that influences solar panel insolation. The points can be created as set of points distributed along the given path or grid. Each point represents a potential solar panel location, numbered from to . Buildings and points are referenced inside the Grasshopper (Rhinoceros plug-in), a visual programming language, and visualised into Rhinoceros 3D. Simplified representation of the buildings and potential solar panel locations are presented in Figure 1.

The second phase refers to the automatic change of the orientation of the solar panel inside the Grasshopper. All the

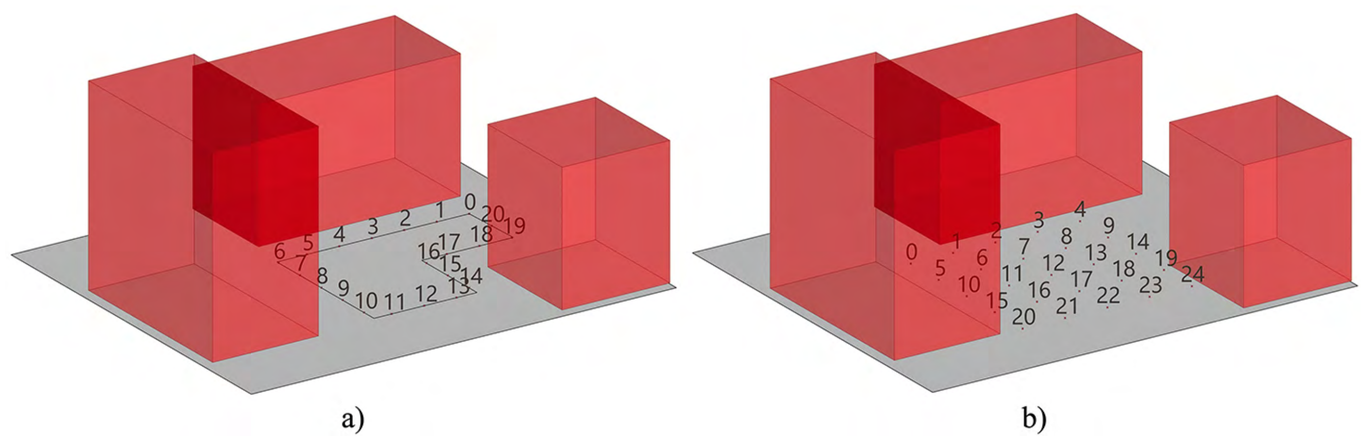

Figure 1. Representation of referenced buildings geometry and potential solar panel locations as a set of numbers distributed along: a) polygonal path; b) grid

possible combinations of locations, tilt and azimuth angles are generated and linked to a solar panel represented as a plane in Grasshopper. Solar panel is generated as a rectangular shape, and its orientation is determined with parameters of tilt angle (β) and azimuth angle (γ). The tilt angle β rotates around *y-axis* and its value varies from 0° (horizontal surface) to 90° (vertical surface), for the step of 1° where 0° $\leq \beta \leq$ 90. The azimuth angle γ, rotates around the z-axis and its value varies for the full circle rotation from 0° to 359°, for the step of 1°, -180° $\leq \gamma \leq$ 180°. The azimuth angle is measured clockwise, with zero due south, -90° for eastward, +90° for westward, and ±180° for northward-oriented surfaces (Figure 2). The number of tilt angles is 91 (0-90) and the number of azimuth angles is 360 (0-359).

The process for automatically changing solar panel tilt and azimuth angles in order to maximize solar panel insolation was created. To examine all combinations of tilt and azimuth angles for a solar panel, the number of tilt angles is cross-referenced with the number of azimuth angles. The number of combination for one location is multiplication product of all tilt and azimuth angles - 32760. The total number of combinations for all locations is the multiplication product of the number of tilt angles, the number of azimuth angles, and the number of all possible locations.

The third phase is the simulation and calculation of insolation in Ladybug, an environmental analysis software (Grasshopper plug-in). Ladybug can take into account geometry of buildings, weather data and any time and year period of analysis set. The Ladybug software calculates the average insolation of a solar panel in kWh/m^2.

In order to perform the simulation of insolation, it is necessary to introduce a sky matrix value. To calculate the sky matrix value, which describes the radiation coming from each patch of the sky dome, the following input data from the weather file must be considered: location data, such as longitude, latitude and elevation, direct normal and diffuse horizontal radiation and the period of the year. The analysis period of the year can be set to take into account different hour intervals for each month. Since the panel's tilt and azimuth angles are fixed, we analysed the entire year period. The analysis period is chosen from sunrise to sunset for each month (World Data Info, 2023). For this study, the geographical location of Belgrade, Serbia (44°82' N and 20°28' E) was selected. According to the Köppen-Geiger climate classification (Kottek et al., 2006; Fricke et al., 2022), Belgrade has a Cfa climate with a mean annual insolation value of 2112 hours, a maximum monthly value in July with 291

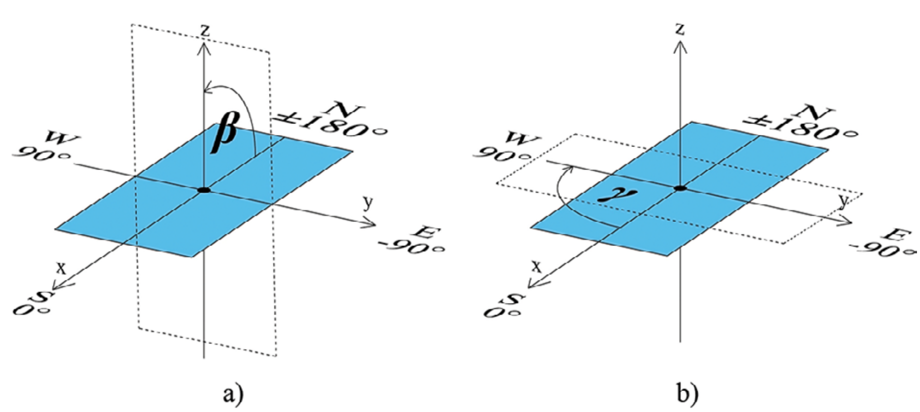

Figure 2. Solar panel a) tilt angle b) azimuth angle

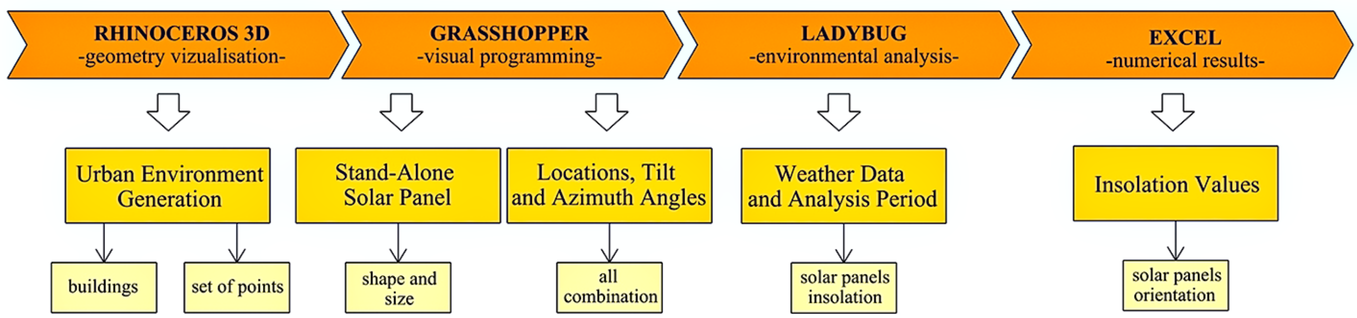

Figure 3. Workflow representation based on the used CAD software applications

hours, and a minimum in December with 65 hours (Stojaković et al., 2020).

The solar simulation is performed for each combination of tilt and azimuth angles at one location. 3D geometry of the buildings is fixed on site, whereas the tilt and azimuth angles are automatically changed and solar simulation are performed. When the solar simulation is finished for one fixed tilt and one azimuth angle, the process repeats solar simulation for the same fixed tilt and another azimuth angle. The process lasts until the list of all combination of the tilt and azimuth angles is finished. A list of insolation values is created for each combination of tilt and azimuth angles for one solar panel location. The maximum insolation value implies the optimal orientation of the solar panel for given location. After calculating the insolation values at one location, the location of the solar panel automatically changes, and a calculation of the insolation values for each combination of tilt and azimuth angles at a new location is performed. The process calculates insolation values until all predetermined solar panel locations are examined.

The fourth phase is the export of all numerical results in order to detect the all values of insolation, which corresponds to the certain location and orientation of the solar panel for a created courtyard, selected location, weather data and analysis period.

The workflow of the designed approach is presented in Figure 3, illustrating the relationship between various CAD software applications. The proposed approach for evaluating solar panels insolation in urban courtyards takes into consideration 3D creation of buildings and points, which is done in the Rhinoceros software environment. In the Grasshopper, visual programing software application, the parametric definition for automatically changing solar panel orientation and location was created. The geometry of solar panel with certain tilt and azimuth angles appears into Rhinoceros as a surface that receives the solar energy. Geometry of the buildings, solar panel and weather data are used in the Ladybug, environmental software application, performing calculation of solar panels insolation. In the end the data is imported into Excel for statistical data analysis, comparison and detecting optimal solution.

Results and Discussion

Method presented in previous section is further tested on two case studies. First , the influence of building height and orientation of generic rectangular block is tested in order to demonstrate the variability of solar panel insolation improvement depending of the environment properties. After that, the method is applied to the example that demonstrates it's ability in urban courtyard design.

A simple urban block with courtyard

To test the intensity of the shade from surrounding buildings on the insolation of solar panels, we initially conducted a test on a simplified urban block with courtyard. This test is done to demonstrate the approach application and to investigate how variability of the surrounding buildings influence the distribution insolation improvement. Buildings are situated on a flat surface and form a square courtyard, measuring 30 m × 30 m. Four buildings are positioned around the courtyard. In this example a standard 72 cell configuration of rectangular solar panel measuring 1.9 m (length) by 1 m (width) (Solar Panel Size, 2023) is used. The distance between the center of the solar panel and the ground level is 4 m.

The influence of the height of buildings on solar panels insolation

In order to detect the range of building heights that have a significant influence on the insolation values of solar panels, we used a simple closed urban block measuring 30 m × 30 m. The heights varied from 0 m to 60 m. Nine panels were evenly distributed between buildings. The average insolation of a panel is calculated for different (mutually equal)

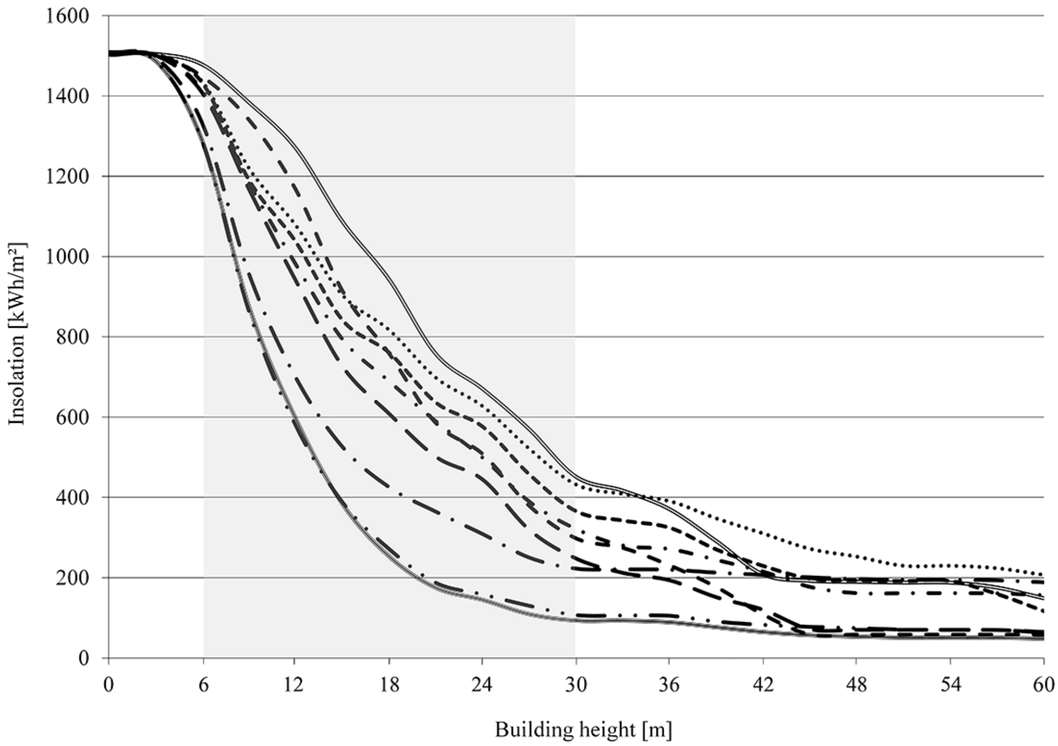

Figure 4. Correlation between buildings heights and solar panel insolation

building heights. The influence of building shade for all nine panel locations is shown in Figure 4. When the buildings' height is lower than the height of the panels, all solar panels are exposed to solar radiation all the time, and building shade has no effect. On the other hand, when the buildings' height is above 30 m, the solar panels are mostly in the shade, and the average insolation varies from 2.3% to 20% of the maximum insolation value. Due to this analysis, building heights of less than 6 m and greater than 30 m are considered irrelevant for this urban block morphology.

Table 1. The type of variations with corresponding building heights

Variations									
I	II	III	IV	V	VI	VII	VIII	IX	X
Buildings heights [m]									
30	15	21	30	21	15	6	6	21	30
6	6	15	21	15	30	15	21	6	15
15	21	30	6	6	21	21	30	15	6
21	30	6	15	30	6	30	15	30	21

The influence of tilt and azimuth angles on the insolation of solar panels

The tilt and azimuth angles of solar panels are the most significant factors influencing the insolation level. To evaluate the solar panel insolation obtained by a parametric approach and according to general rule, we tested geometric variations of a simple urban block:

– Variation of building heights, and
– Variation of block orientation in relation to the west-east direction.

For the same simple urban block, ten variations (I-X) were created with variable building heights of 6 m, 15 m, 21 m and 30 m (Table 1).

Heights were assigned to each building, based on the results obtained in the previous analysis. This simple urban block is further oriented into three different directions (Figure 5a, 5b and 5c). Sixteen potential solar panel locations are evenly distributed across the courtyard of an urban block. A total of 30 variations of a simple urban block were made, each with sixteen panels. This makes a total of 480 panel simulations for a simple urban block. For each panel, simulations of tilt and azimuth angles are performed.

For the selected geographical location (Belgrade, Serbia), according to the general rule, the tilt angle of fixed solar panels is the value of the latitude (β = 45°) with an orientation to the south (γ = 0°). To evaluate the improvement of insolation, the best insolation values obtained by the parametric approach and the insolation values of panels oriented according to the general rule (β = 45°, γ = 0°) were compared.

A histogram showing the improvement for panels in all variations is presented in Figure 6. In most cases (66 % of all cases), the improvement was between 0.5 % and 25 %,

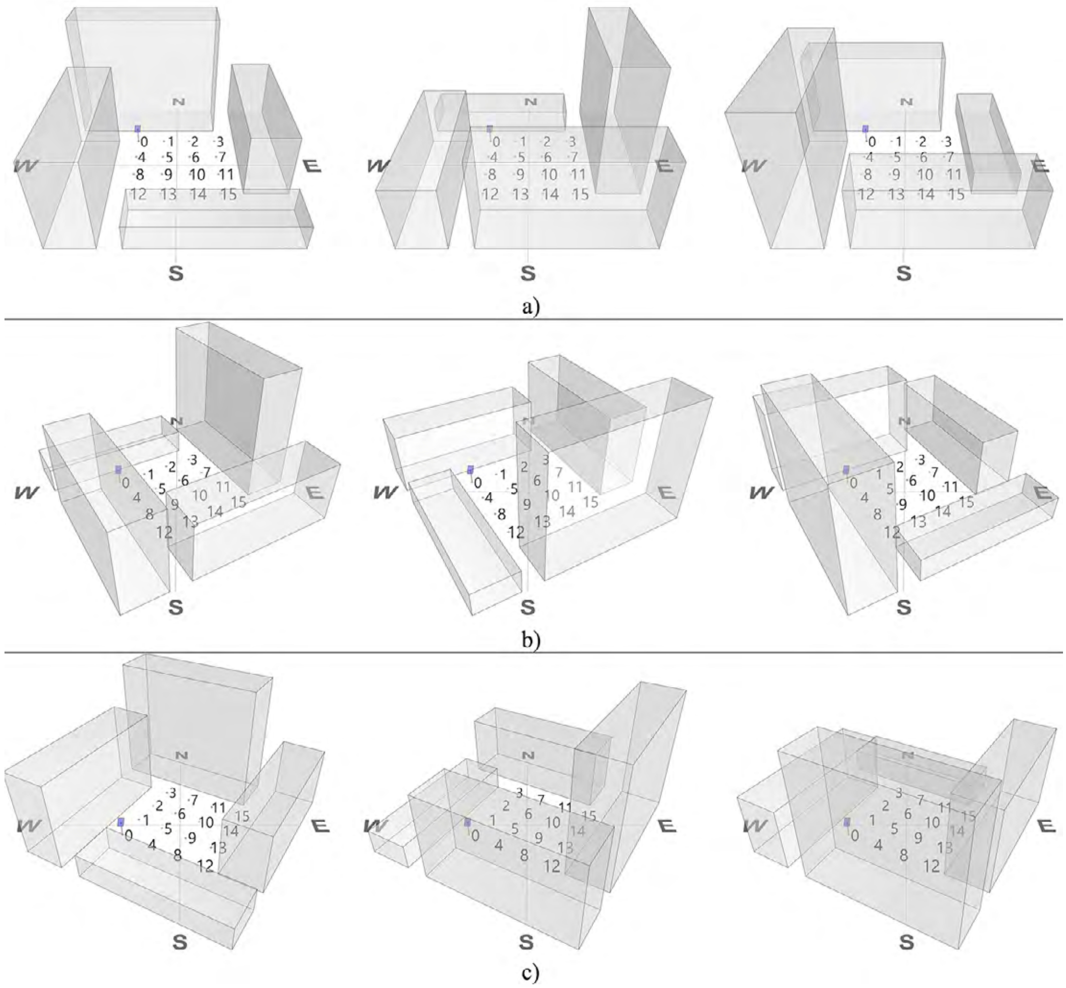

Figure 5. Examples of different variations of simple urban block oriented into direction: a) N-S; b) 30° NW-SE; c) 60° NW-SE, with sample of solar panel orientation at location no. 0.

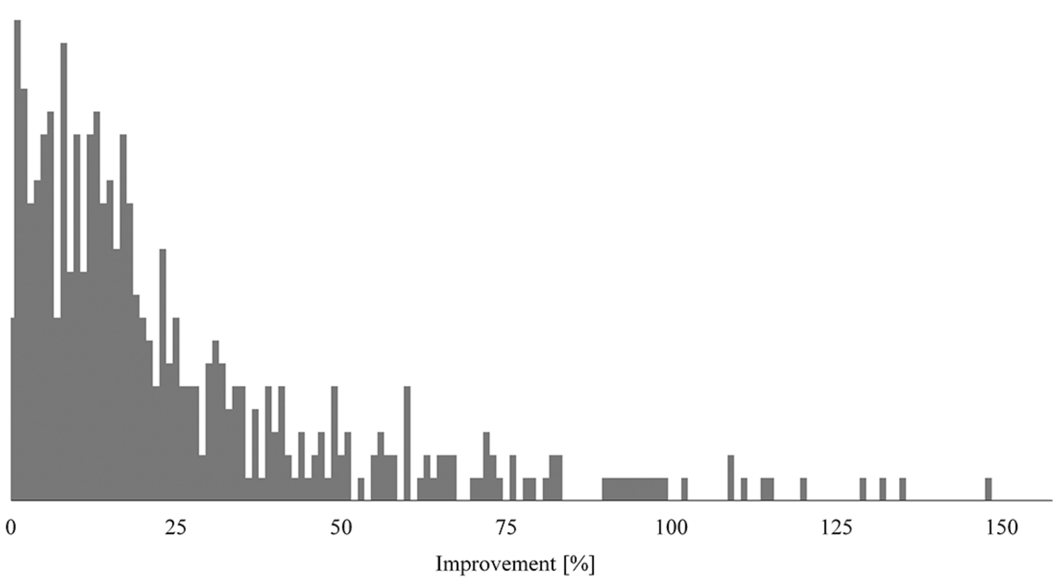

Figure 6. Percentage of insolation improvement for each panel in all variations after the use of the parametric approach in the simple urban block with courtyard

while in some cases (32.3 % of cases), the improvement is much higher, ranging from 25 % to 148 %. Only 1.7 % of the cases had an improvement of less than 0.5 %.

The average improvement for each urban block variation ranges from 45.71 kWh/m² to 169.31 kWh/m², which is from 4.3 % to 29.6 % better than the insolation values of panels oriented according to the general rule. The average insolation improvement in all variations is 116.68 kWh/m² (18.3 % with a standard deviation of σ = 8.2 %). The improvement depending on the variation of building height and rotation angle of simple urban block is shown in Table 2.

Courtyard surrounded by real buildings representation

We apply the approach to another courtyard design and examine its potential for creating layout with certain number of solar panels with maximal insolation. The proposed approach for optimizing the tilt and azimuth angles for potential locations of solar panels, was applied on an urban block with a real buildings representation with a courtyard (Figure 7a). In the middle of the open space between the buildings, there is a hexagonal playground, and solar panels have to be located around it. Twelve possible solar panel locations are specified with

Table 2. Improvement of solar panel insolation according to the parametric approach and according to general rule with different orientation of the simple urban block with courtyard

Buildings heights variation	Orientation of the simple urban block	Parametric approach	General rule	Improvement	
		[kWh/m²]	[kWh/m²]	[kWh/m²]	[%]
I	N-S	921.51	792.77	128.75	16.24
II		741.77	572.46	169.31	29.58
III		803.47	670.55	132.92	19.82
IV		1100.72	1055.01	45.71	4.33
V		1001.21	936.30	64.91	6.93
VI		851.67	705.63	146.04	20.70
VII		609.15	485.28	123.87	25.53
VIII		609.65	476.52	133.13	27.94
IX		870.20	716.09	154.11	21.52
X		1078.89	1022.06	56.83	5.56
I	NW-SE	786.25	665.07	121.18	18.22
II		621.11	480.57	140.53	29.24
III		899.56	799.04	100.52	12.58
IV		1087.54	1017.63	69.91	6.87
V		941.37	824.14	117.23	14.22
VI		987.31	883.55	103.76	11.74
VII		600.90	473.72	127.18	26.85
VIII		690.22	552.26	137.97	24.98
IX		726.89	584.73	142.16	24.31
X		1014.99	914.06	100.93	11.04
I	NW-SE	702.34	585.79	116.56	19.90
II		569.07	445.43	123.64	27.76
III		953.11	904.94	48.17	5.32
IV		1015.23	898.37	116.86	13.01
V		814.34	656.98	157.36	23.95
VI		1061.58	1006.05	55.54	5.52
VII		657.74	510.56	147.18	28.83
VIII		820.82	683.63	137.18	20.07
IX		618.69	487.43	131.25	26.93
X		915.47	765.74	149.73	19.55

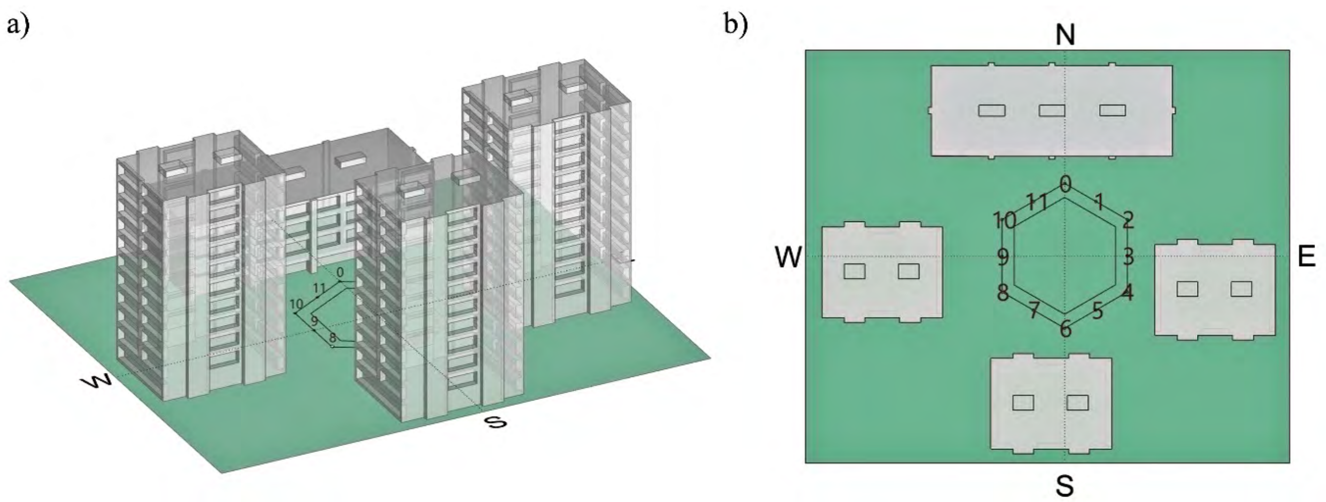

Figure 7. a) 3D view of courtyard with surrounding buildings. b) Top view of courtyard with potential solar panel locations

the same distance from the edges of the playground (Figure 7b).

In this urban area it is observed that the optimal tilt angles β and azimuth angles γ of the solar panel for each location are different, which is not aligned with the general rule ($\beta = 45°$, $\gamma = 0°$). The distribution of the insolation levels for panel orientation on twelve locations is shown in Figure 8. Optimal angles (the maximum point of the function) are displayed in the image for each panel.

According to the numerous studies (Chang, 2010; Stanciu & Stanciu, 2014; Asowata et al., 2012) in the northern hemisphere, the optimal orientation for stand-alone solar panels is south facing and optimum tilt angle would be same as the latitude angle of the location. The optimal tilt and azimuth angles that are presented in the Table 3 indicates that the greatest improvements of solar panel insolation is made when the solar panel is tilted and oriented at optimum angles are $\beta = 5°$ and $\gamma = -60°$. It is obvious that

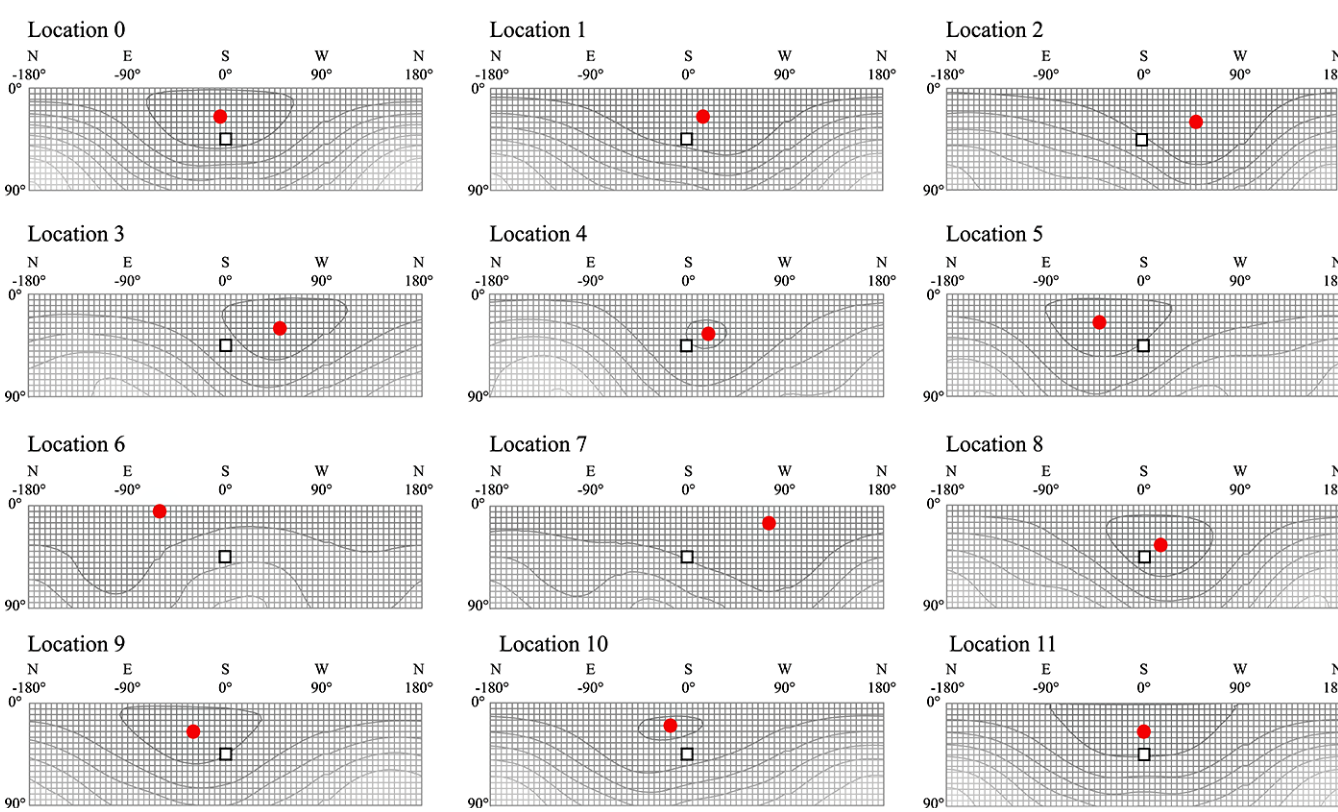

Figure 8. Distribution of insolation levels depending of the tilt and azimuth angles. Red circle shows maximal insolation obtained by approach and black square shows the values recommended by general rule

Table 3. Solar panels insolation during the entire period of the year at potential locations. The maximal insolation is at location no. 0

Location	Parametric approach			General rule		[%]
	Maximal insolation [kWh/m²]	β [°]	γ [°]	Maximal insolation [kWh/m²]	[kWh/m²]	
0	839.74	28	-1	839.74	36.54	4.35
1	735.38	25	15	735.38	59.41	8.08
2	686.46	30	50	686.46	100.56	14.65
3	568.77	30	50	568.77	74.95	13.18
4	594.42	35	20	594.42	15.41	2.59
5	594.95	25	-40	594.95	38.43	6.46
6	325.98	5	-60	325.98	125.35	38.45
7	505.01	15	75	505.01	79.3	15.7
8	731.94	35	15	731.94	16.08	2.20
9	702.14	25	-30	702.14	45.24	6.44
10	747.7	20	-15	747.7	62.38	8.34
11	806.42	25	0	806.42	50.65	6.28

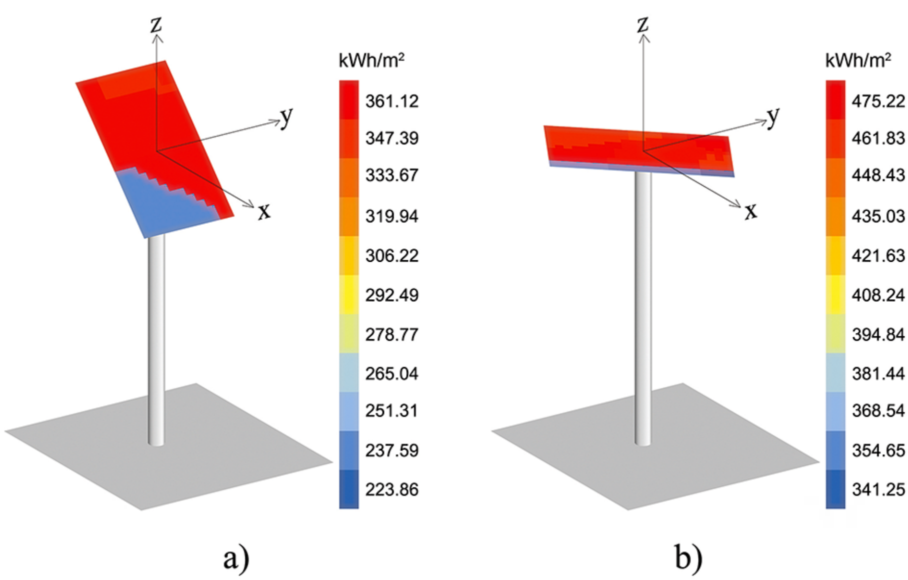

Figure 9. 3D view of solar panel insolation for location no.6 oriented according to: a) general rule; b) the parametric approach

general recommendation from the literature cannot be applied for solar panels in built-up urban areas, due to buildings affect the shading of the solar panels.

The average improvement of solar panel insolation obtained by the parametric approach for the entire year period, compared to orientations commonly used in practice, is 58.69 kWh/m², representing an 10.6 % improvement. The most significant improvement in solar panel insolation was observed at location no. 6, with a value of 125.35 kWh/m² (38.45% better than the insolation value of a panel oriented by the general rule).

In order to illustrate the solar panel insolation for location no. 6, the 3D view of solar panel is presented in Figure 9a and 9b.

The maximum insolation of the solar panel is detected at location no. 0 with a tilt of β_{opt} = 28° and an eastward orientation of γ_{opt} = -1°. The improvement of solar panel insolation for location no. 0 is 36.5 kWh/m², corresponding to a 4.35 % better result than the insolation value of a panel oriented by the general rule.

In cases where solar panel orientations can be adjusted during the year, optimization can be done separately for

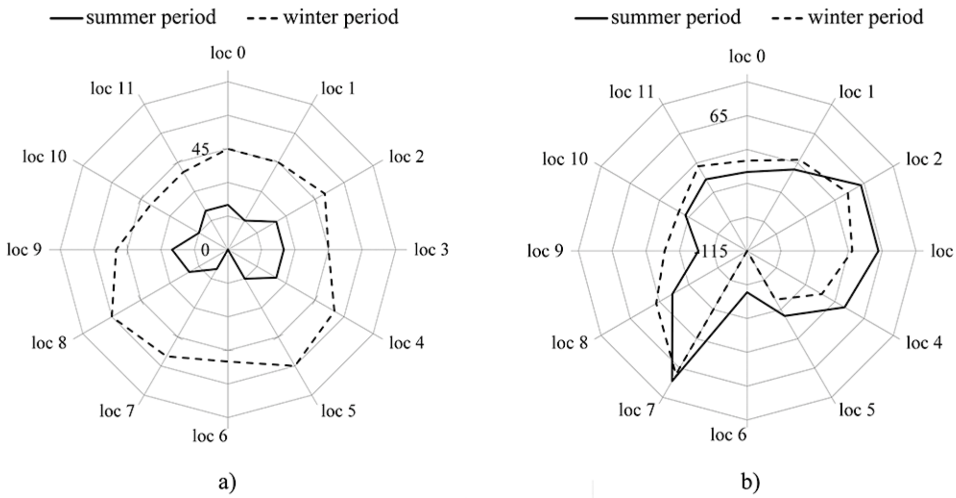

Figure 10. Comparison of the optimal: a) tilt angles; b) azimuth angles for summer and winter period

different periods of the year (seasons or months). We conducted analyses for two year segments, summer months and winter months. Optimal tilt angles for the summer period range from 0° to 25°, and for the winter period, from 40° to 60° (Figure 10a). Azimuth angles for both periods varied in the same range, from 85° to south and from south to -110° (Figure 10b). The similar results noticed in numerous studies (Duffie et al., 2020, Shariah at al., 2002; Hussein at al., 2000) where suggested and concluded that the optimum tilt angle (β_{opt}) is taken to be equal to the latitude of the location (φ), while for summer $\beta_{opt} = \varphi$+15° and for winter $\beta_{opt} = \varphi$-15°.

The average improvement in the summer period is 14.4 % (with a standard deviation of $\sigma = 7.6$ %), and in the winter period, it is 10.7 % (with a standard deviation of $\sigma = 18.2$ %).

Distribution of solar panels along the simple polygonal shape

In urban planning practice, the certain number of solar panels should be placed in urban area on equally mutual distance. In previously analyzed block, three solar panels should be placed in a layout around the playground, spaced evenly. The maximum insolation value for all locations is shown in Figure 11a. We analyzed the total insolation for layouts in which nearby panels are separated by at least two 'empty' locations. All possible layouts of panel locations are presented in Table 4.

The best layout that provides the maximum insolation value suitable for three solar panels for summer and winter months is locations no. 2, 8, and 11 (Figure 11b). The total insolation of this layout is 12% higher than the average maximal insolation for all other layouts. The insolation of solar panels oriented by the general rule is shown in Figure 12a, and insolation of solar panels oriented by the approach is shown in Figure 12b.

For all combinations of three panel locations and for a whole year period, compared to the average insolation value of solar panels that would be oriented in the same locations according to the general rule, the average improvement is 9.18%, with a standard deviation of $\sigma = 3.8$%. Rhinoceros software and its existing plug-ins and add-ons enable the optimization of urban parameters and urban elements design and position with various optimization techniques by using the parametric approach. This is an advantage compared to many software applications, such as Matlab and PVsyst (Benghanem, 2011; Shrivastava et al., 2023) that cannot be applied to optimize additional urban elements and they are limited only to estimate the energy yield and optimize the solar panels system design. Hence, the urban planning strategies and designs problems can be solved and carried out in a sophisticated manner by using parametric tools suitable for architects and urban planners.

Taking into account that solar panels provide shade, they are used to find optimal benches locations. In order to use optimal solar panels layout obtained by parametric approach, we propose additional procedure for optimizing benches near the solar panels. The solar panels and surrounding buildings can provide shade for benches during the hottest summer period (June, July, and August, from 10 UTC to 19 UTC). After positioning the solar panels, we identified the optimal location for benches to be placed near selected solar panels and oriented towards the playground area. A predefined set of 166 bench locations is arranged as points along the lines around the solar panel. Each bench's potential center point is connected with the corresponding point representing its location. The geometry of the bench is automatically adjusted as locations change, and simulations of insolation are performed. Therefore, after each alteration in bench location, the bench's insolation is calculated. The minimum insolation value corresponds to the optimal bench location (Figure 13).

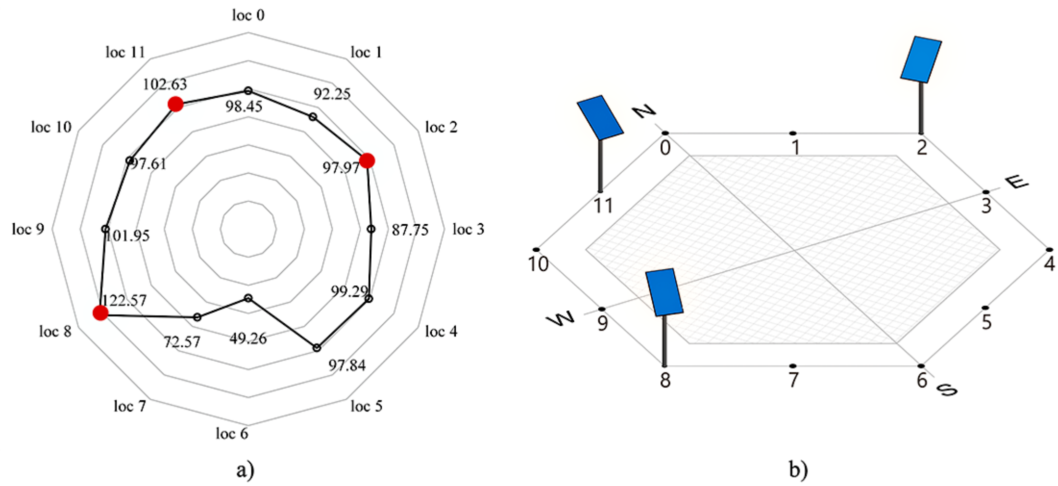

Figure 11. a) Maximal panel insolation for all locations. Selected combination is marked with red circles. b) Solar panel positions with maximal insolation level for whole year period at locations no. 2, 8 and 11

Table 4. Insolation for different combinations of three solar panel locations

Locations	Parametric approach	General rule	Improvement	
	[kWh/m²]	[kWh/m²]	[kWh/m²]	[%]
0 4 8	744.71	722.03	22.68	3.14
1 5 9	725.18	677.49	47.69	7.04
2 6 10	682.81	586.71	96.1	16.38
3 7 11	695.03	626.73	68.3	10.9
0 3 8	756.01	713.48	42.53	5.96
0 5 9	752.34	712.27	40.07	5.63
1 4 9	717.31	677.29	40.02	5.91
1 6 10	685.41	603.02	82.39	13.66
2 5 10	743.49	676.37	67.12	9.92
2 7 11	742.81	665.96	76.85	11.54
3 6 10	635.04	547.48	87.56	15.99
3 8 11	749.61	702.37	47.24	6.73
4 7 11	683.73	635.28	48.45	7.63
4 9 0	744.49	712.11	32.38	4.55
5 8 1	725.39	687.42	37.97	5.52
5 9 2	722.56	661.14	61.42	9.29
6 9 1	664.51	587.83	76.68	13.04
6 11 3	650.71	567.05	83.66	14.75
7 10 2	727.13	646.39	80.74	12.49
7 0 3	701.43	637.84	63.59	9.97
8 11 2	797.37	741.61	55.76	7.52
8 1 4	717.54	687.24	30.3	4.41

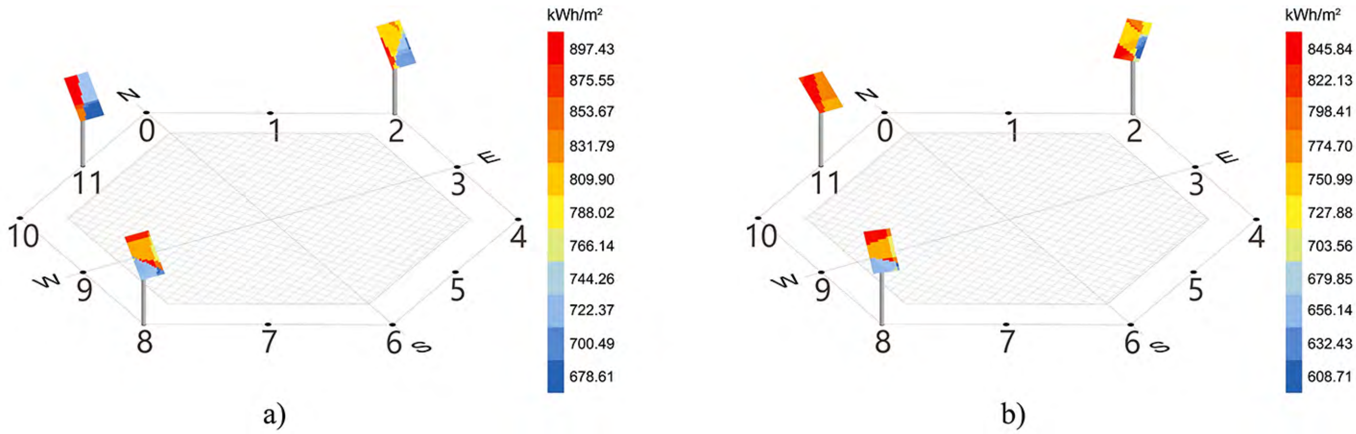

Figure 12. 3D view with insolation simulation of solar panels oriented by: a) general rule; b) the parametric approach

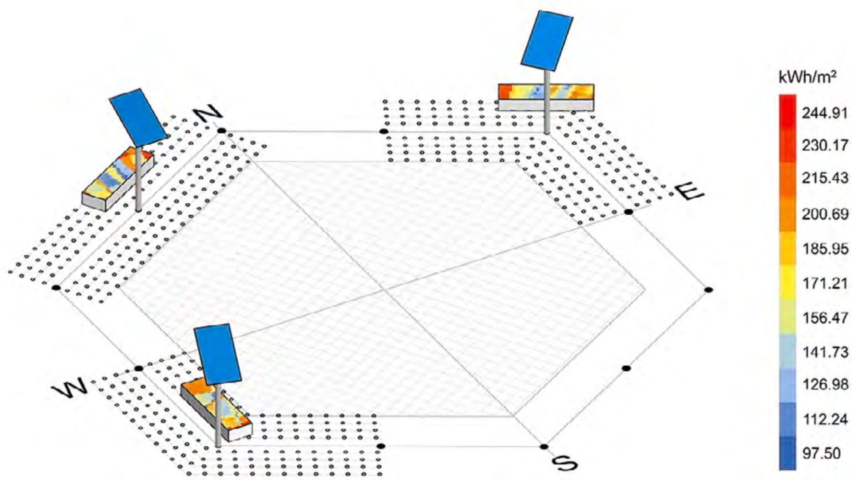

Figure 13. Locations of the benches with minimal insolation level

Insolation values for all bench locations around solar panel locations no. 2, no. 8, and no. 11 are shown in Figures 14a, 14b, and 14c, respectively. The minimum insolation of the bench positioned around solar panel location no. 2 is 187.74 kWh/m², for the bench placed around solar panel location no. 8 insolation is 136.62 kWh/m² and for the bench positioned around solar panel location no. 11, the minimal insolation value is 196.68 kWh/m². Distribution of the insolation levels in all bench locations is shown in Figure 14 and it can be noticed that if the bench would be placed without prior simulation it would be likely that the insolation would be higher. In optimal positions bench is 30%, 32% and 25% less insolated than in the worst case and 17%, 20% and 16% compared to average value (for solar panel locations no.2, no. 8 and no. 11 respectively).

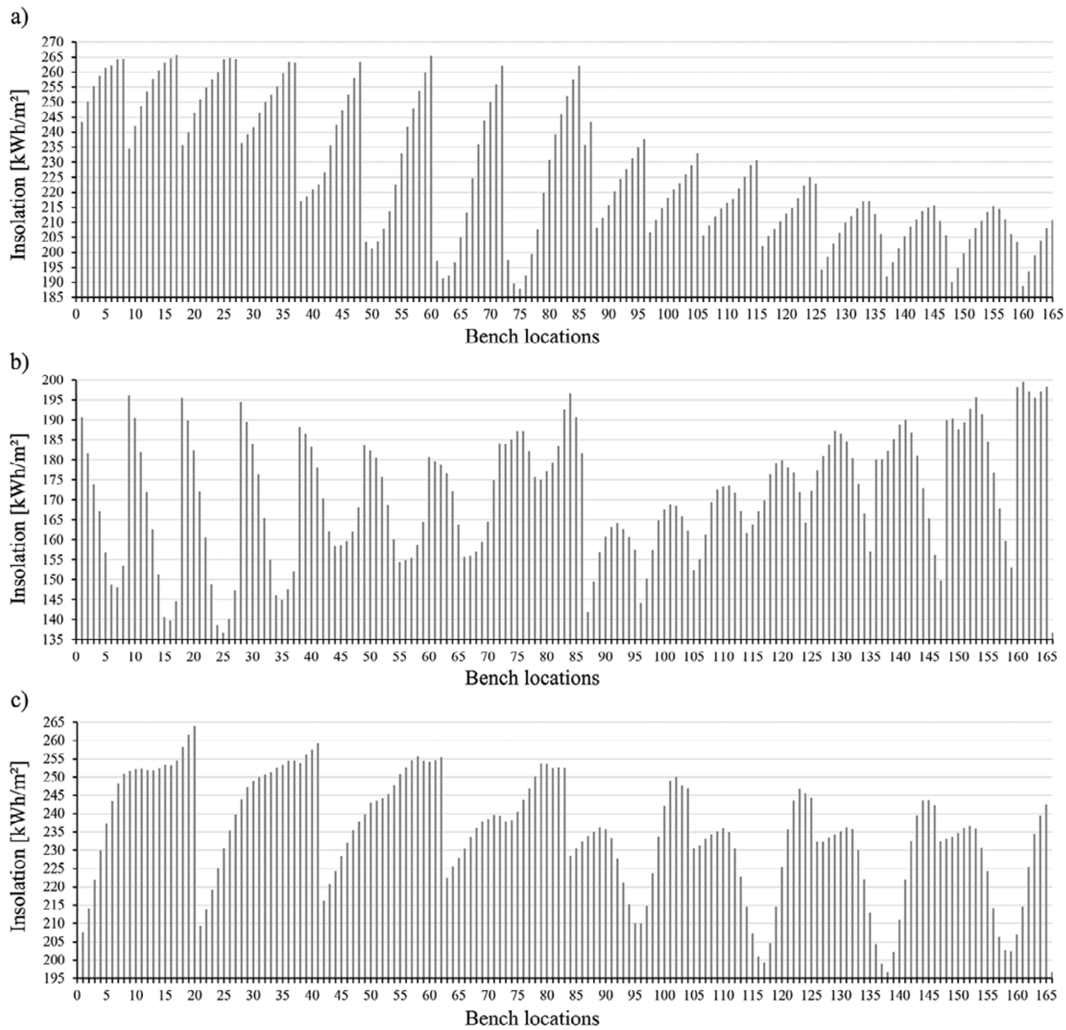

Figure 14. Insolation values of bench placed near solar panel location a) no. 2; b) no. 8; c) no. 11

Conclusion

In this research, it is demonstrated how a parametric approach for changing the location and orientation of stand-alone solar panels, can be used to create environmentally conscious urban design and can be used to improve the insolation of a solar panels and other urban elements. The method proposed in this study has the possibility to incorporate several input data, including a 3D model of surrounding buildings, solar panel geometry and potential solar panel locations, and various weather data simulating diffuse radiation measured for a specific geographic location. This enables the application of the proposed approach to any built-up urban area. The approach illustrates how digital technologies and a combination of different CAD software applications for 3D modeling, parametric modeling, and solar simulations, familiar to architects and urban planners, can be efficiently used to develop optimization guidelines applicable in urban planning practice. Introduce other urban elements in urban courtyard design needed for urban planning process by using results of solar panels orientation and location is the crucial advantage of this approach, compared to the models that only quantify the solar energy potential of photovoltaic systems, which are limited to estimate the energy yield and optimize the solar panels system design. Furthermore, our approach is a valuable contribution for urban planning strategies in the beginning of urban design process in order to create comfortable open spaces for residents.

The results of this research contribute to the understanding of the importance of adequate stand-alone solar panel distribution in open urban courtyards. Using this approach, an improvement in solar panel insolation of up to 38% was observed compared to the solar panel insolation that would be achieved if the panel was oriented according to the guidelines applied in practice. The results show that the application of the parametric approach increases the possibility of solar panel insolation for different scenarios: fixed (simulations for the entire year), non-fixed solar panels (simulations for different seasons), and solar panel layout. The optimal orientation and location of solar panels influence the overshadowing of other urban elements, such as bench.es. Therefore, selecting the best orientation and location of the benches contributes to favorable comfort conditions in open urban spaces. The possibility of creating sustainable urban environment by using various urban elements such as solar panels and benches is shown. Their adequate integration into current urban design and infrastructure is important for creating healthier and more sustainable urban spaces for local communities and future generations.

A limitation of approach presented in this paper is that although the influence of trees could be added, it can only be presented as a full shadow casting solid, meaning that characteristics such as crown density, leaf transparency and foliage period cannot be taken into calculation. It is only possible to generate trees as solid forms that cast a full shadow.

In future research, we intend to use the proposed approach for optimizing various urban parameters. A large area of solar tree with multiple panels acting as non-transparent structure, cast a full shadow and can mitigate overheating of urban areas, such as playgrounds, parking lots, and footways. By employing multi-objective optimization process, we aim to optimize simultaneously the maximal insolation of the solar tree and minimal insolation of the urban area.

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