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SolarPW: A new solar design tool to exploit solar potential in existing urban areas

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Abstract

This paper aims to show a new solar design tool that can be used to optimize the building's shape and solar access in existing urban areas. The presented methodology was used for the analysis of the Surfers Paradise in Queensland, where in the past the urban and buildings development changed completely the morphology of the city. Since in the medium term the Zero Energy building will be the standard for new constructions, urban development should follow the Integrated Sustainable Design approach and the principles of solar design in order to exploit solar radiation using PV modules and Solar thermal collectors in the building envelopes. The tool is based on Matlab algorithm and on RADIANCE-DAYSIM, a dynamic simulation tool, and can help urban designers and architects since the first design phase.

Keywords: Solar potential; solar energy; photovoltaic panels; solar thermal collectors

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1. Introduction

Our cities have been undergoing continuous transformation and adaptation processes to adapt to demands from their inhabitants. Population growth on one side and environmental problems on the other, have created new demands, to which the city has to answer. In addition, the economic crisis has given another dimension to these complex problems. Among these, the new Energy Performance Building Directive (2010/31/EU) requires that new buildings comply with the "nearly zero energy" standard by 2020 [1]: different researches [2][3] demonstrate that the zero energy annual balance can be reached, with

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a combination of a conscious design strategy, good performance of the building envelope, and exploitation of energy from renewable sources, such as photovoltaic systems, to reduce the environmental impact and secure future supply of energy [4][5]. Nowadays more than three-fourths of the world's population lives and works within cities, where up to 80% of all available energy is consumed and over half of greenhouse gas emissions are produced [6], so the improvement of the energy efficiency of cities is central to the de-carbonisation of economy. A new approach is then required to design new buildings with particular attention to volume, shape, orientation and with larger use of the renewable sources integrated in the envelope, paying attention to the relationship between the building and its urban context.

However, if the feasibility of energy autonomy and optimized use of renewable sources has already been demonstrated for isolated buildings, the implications of energy efficiency and of mutual relationships among buildings in neighbourhoods are still to be fully understood.

This research work investigates the relationship between urban morphology and energy consumption, knowing that the energy efficiency of cluster of buildings is completely different than the performances of isolated ones.

This paper sketches out some new basic design principles suggesting the use of a tool to support the use of solar energy as one of the measures that can improve the energy efficiency of districts.

2. Material and method

This work starts from the global scenario to give indications about the influence that building and façade design has on the total amount of solar radiation (direct, diffuse, reflected) incident on the external building envelope. Optimizing the shape of buildings in the district morphology may in fact lead to increased energy production from integrated solar systems. The influence of the distribution of volumes on the overshadowing among buildings and on solar access has been assessed and validated through different tools. In the preliminary analysis, Ecotect [7] was used to study the overshadowing effect. In the second part of the study, Daysim [8], a dynamic daylighting simulation tool, was used to evaluate global solar radiation incident on the building envelope and its increment or decrement with respect to the optimized shadowing conditions.

These analyses were performed on an area of the coastal city of Gold Coast, Surfers Paradise, located in the South East of the Queensland state, Australia. Surfers Paradise is the second most populated city of the state [9], with a growing amount of population. The conspicuous morphological feature of Gold Coast, as well as other cities in South Eastern Queensland, is a dispersed and diffused pattern, with high-rise buildings in the strip close to the sea.

3. Theory and calculation

This paper presents the initial stages of development of a new solar design tool that it is possible to use for both new developments and existing areas. The Solar Potential poWer tool (Solar PW) aims at improving solar access in dense urban districts and optimizing the shape of buildings to harvest solar radiation. In this way, it may contribute to increasing the potential of using PV panels or solar thermal collectors integrated in the building envelope to produce clean energy.

The study started from the analysis of simple models of two adjacent residential buildings in which different parameters are considered: height and size of the buildings and distance between blocks.

The first part of the work analysed the influence of the overshadowing created by one building on the opposite façade of the other. All simulations have been performed in Ecotect using the weather data file of Brisbane (lat. -27°38E, long. 153°17N). The analyses included different ratios of building heights (h_1/h_2) and of distance and height (d/h_2), for an azimuth varying in steps of 22.5

degrees from -135 to 135 degrees from the North. Analyses considered direct solar radiation only.

The graph in Fig. 2 summarizes the results: once the ratios h_2/h_1 and d/h_2 are known, following the corresponding line it is possible to know the percentage of shading created by the building with h_1 on the façade of building with height h_2.

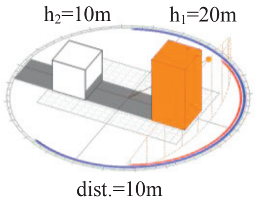
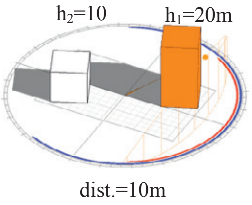
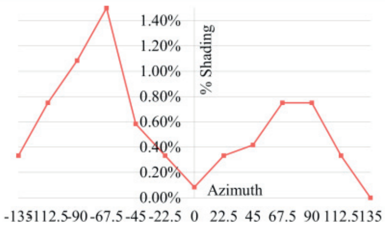
		
Simple model with azimuth angle direction equal to 0	Simple model with azimuth angle direction equal to 22.5 °	The trend of the % shading for different zenith and azimuth on the building (h_2) with h_2/h_1=2 and d/h_2=0.5

Fig. 1. Example of simple model analysis: annual solar direct radiation simulations for different azimuth angle direction with ratio h_2/h_1=2 and d/h_2=0.5: h_1 represented the height of the building volume projecting its shadow on building volume with height equal to h_2

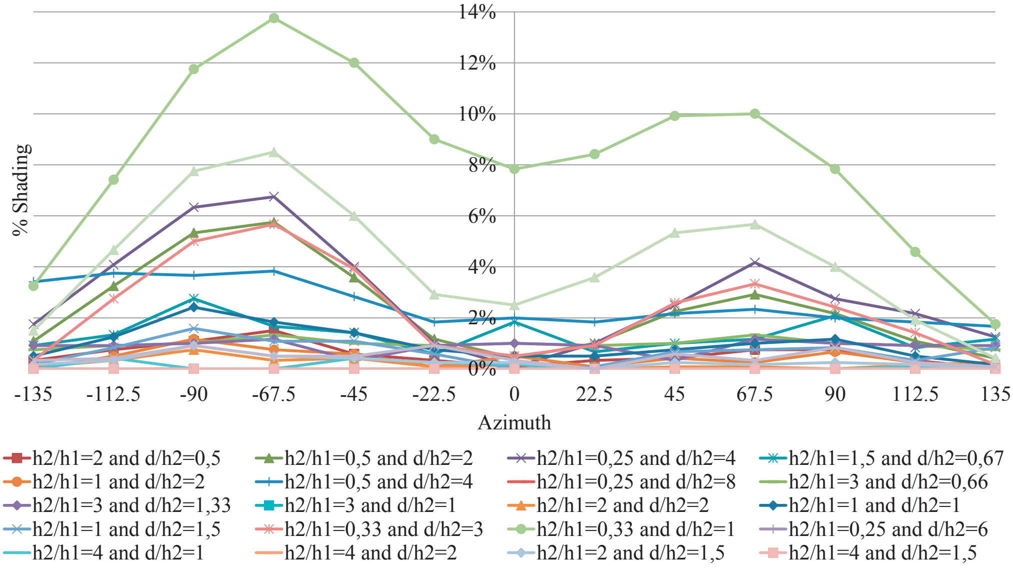
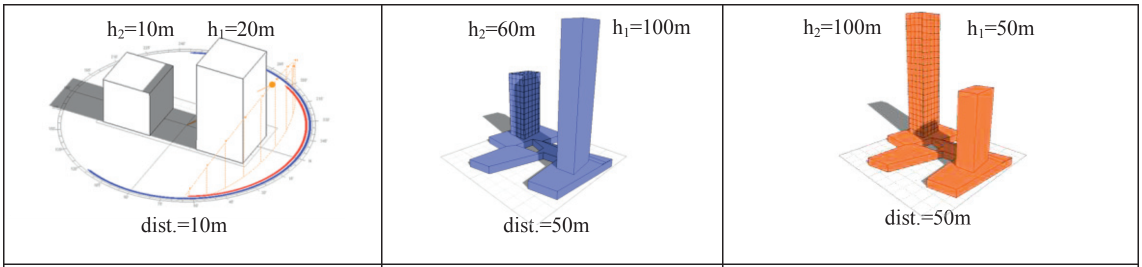


Fig. 2. Trends of the % of the façades in shade vs azimuth, for different height and distances' ratios.

The building volumes of a case study in Surfers Paradise were analysed in two different scenarios: the designed scenario – the outcome of a workshop organized in Gold Coast from 10th to 23rd of July, 2011 by Politecnico di Milano, University of Queensland, University of New South Wales and Griffith University – and the solar optimized scenario, created through the tool elaborated from simple models analyses and systematized with a Matlab algorithm [10]. The optimization of volumes starts considering the closest value ratio (d/h_2) of the examined couple of buildings with respect to the simple models (two rectangular boxes with different heights). From the corresponding shadow graph it is possible to optimize the relative heights of the buildings in order to increase the annual direct solar radiation for the highest façade, at different zenith and azimuth values and different h_1/h_2 and d/h_2 ratios.

Fig. 1 shows an example of optimization using this method: the graph relative to the simple case with d/h_2 ratio equal to 0.5 and azimuth angle direction from buildings equal to 0° was used. The corresponding simple model minimizing the influence of shadows on the buildings is the case study with h_1/h_2 ratio equal to 2 and d/h_2 equal to 0.5. The design situation presents an h_1/h_2 ratio of 0.6, d/h_2 equal to 0.83 and an azimuth angle direction of 0°. Using the graph of the closest available ratio for the corresponding simple model (in this case d/h_2 equal to 0.5, as shown in the rectangle on the right in Fig. 1) it is possible to derive the h_1/h_2 ratio minimizing the overshadowing effects.



Simple model: 0,08% shading on h_1

Design scenario: 10% shading on h_1

Solar optimized design: 0,08% shading on h_1

Fig. 3. Results of one example of the optimization of buildings volumes using the simple model tool.

Results of the optimization by using the simple model tool are presented in the Fig. 3.

The accuracy of the tool was validated with dynamic yearly solar simulations using Daysim (Daynamic Daylighting Simulation). Daysim is a validated Radiance-based program [11], developed and validated for daylight calculations of complex transparent systems [12], that combines a backward-ray-tracing algorithm, a daylight coefficient approach and the Perez Sky Model to simulate time series of solar irradiances.

Table 1. Results simulation conducted by using Daysim in design scenario

Conditions		Design scenario isolated		Design scenario (two buildings)		
Façade	Ambient bounces (ab) and ground reflectance (Gr. refl. [%])	Global solar radiation (kWh/year)	(kWh/m^2year)	Global solar radiation (kWh/year)	(kWh/m^2year)	Decrease of global solar radiation [%]
North	ab=0, Gr. Refl.=15	191,065	139	168,590	123	12%

Table 2. Results simulation conducted by using Daysim in solar optimized scenario

Conditions		Solar optimized scenario isolated		Solar optimized scenario (two buildings)		
Façade	Ambient bounces (ab) and ground reflectance (Gr. refl. [%])	Global solar radiation (kWh/year)	(kWh/m^2year)	Global solar radiation (kWh/year)	(kWh/m^2year)	Decrease of global solar radiation [%]
North	ab=0, Gr. Refl.=15	1,284,743	520	1,271,827	515	1%

It was developed by the National Research Council of Canada and the Fraunhofer Institute for Solar Energy Systems in Germany. Radiance files, generated with the graphical interface of Ecotect and including the model scenes, have been imported in Daysim software and dynamic analyses have been run, in order to collect hourly data during the simulated year. The validation of the case study previously analysed with Ecotect is presented in Table 1 and Table 2. First the isolated building with height h_2 has been analysed, and then the couple of buildings together.

Results demonstrated that the percentages in term of solar radiation lost due to the overshadowing are close (differences of about 1-2%) to those extracted with the previous analysis.

A relationship between all analyzed parameters is translated in an analytic formula trough a "Matlab matrix". This relationship was elaborated with solar radiation data, to optimize the exposure of the volume to the sun. The final aim is to create a tool that, based on geographic coordinates, allows to optimally locate buildings in a dense district with respect to heights and distances.

3.1. Matlab algorithm

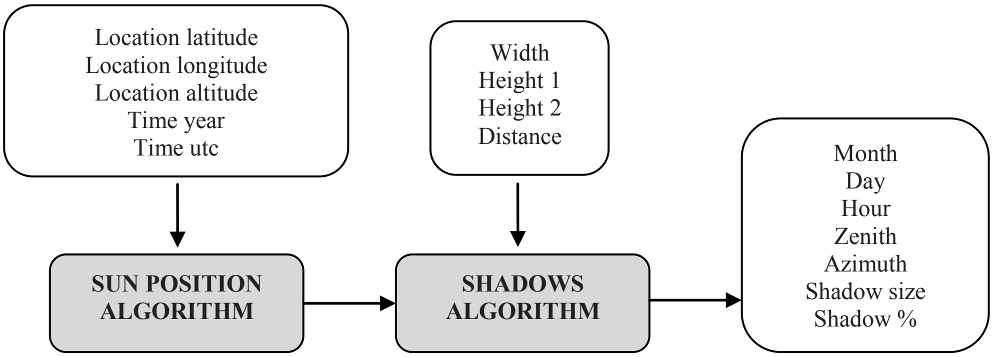


Fig. 4. Block diagram of the Matlab algorithm procedure.

A Matlab algorithm was first developed, in order to evaluate in a simplified way the shadow distribution on two reference buildings, finding key information regarding the optimization of building heights and maximizing direct solar radiation on façades.

The program made use of a sun position algorithm originally developed by Reda and Andreas [13] based on numerical approximations of the exact equations for sun position. The input entries were represented by the location data (latitude, longitude, altitude, year, UTC time) and the geometrical characteristic of the reference buildings (width, height of building 1, height of building 2, distance between buildings). Building 1 represented the building projecting its shadow on building 2.

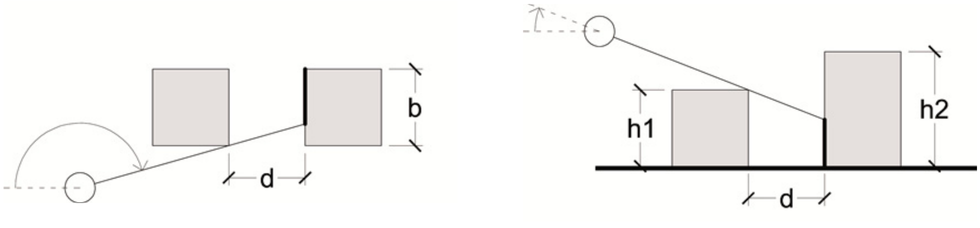


Fig. 5. Geometrical scheme of the Matlab Algorithm operations

By applying the algorithm, a matrix of 8,760 (according to the hourly simulation step) rows was created, listing results as zenith angle (measured clockwise from the horizontal plane), azimuth angle (measured East-wise from the geographical North), size of the projected shadow and percentage of shade on building 2, for every hour of the year. The procedure is shown in the block diagram in Fig. 5. The size of the projected shadow was determined by means of simple geometrical considerations, by splitting it into a horizontal length, governed by the azimuth angle, and a vertical one, depending on the zenith. The negative zenith angles were firstly set equal to zero, in order to avoid taking into account even the shadows projected during the night.

The hourly percentage of shadows on the façade of building 2 was then estimated by dividing the shaded area by the total area.

This algorithm was developed as a fast and easy tool for the optimization of building heights, or building distances. Starting from this basic code, parametric analyses can be carried out, finding useful information for the development of solar design guidelines.

4. Application on the case study

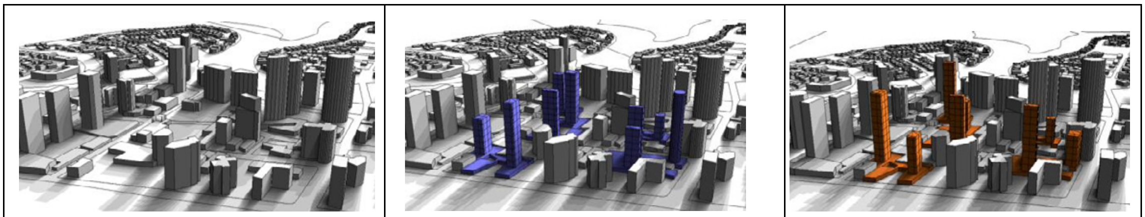
The preliminary tool was applied to different urban contexts, in order to test the analytic relationships found in the simple models. To this purpose, dynamic annual simulations with the RADIANCE software [14] were carried out to assess the solar energy harvested by the buildings. All the solar radiation components (diffuse and direct radiation, sky component and reflections from external surfaces) were considered in this case.

The study investigates the difference in the solar potential of the façades of each single building in the design scenario and in a solar optimized design scenario. In the following analyses only the solar radiation on the façades was considered, excluding the roofs as these have limited surface areas.

The analysis has been conducted in both scenarios: the actual design scenario and the solar optimized design, defined using Daysim. The constant number of façades (capturing surfaces) exposed to solar radiation and the constant total volume of the buildings (new buildings volume) added with respect to the current scenario, have been considered as parameters of the analysis. Table 3 summarizes the parameters in both scenarios. In the first analysis, the raytrace values of ambient bounces was set equal to 0 and the ground reflectance equal to 0%, in order to consider only the effect of overshadowing on the façades of other buildings.

Table 3. Parameters of analysis in designed scenario and solar optimized design scenario

Parameters of the analysis	Actual design scenario	Solar optimized design scenario
Capturing surfaces	47,938 m^2	46,739 m^2
New buildings volume	180,724 m^3	179,263 m^3



Current scenario

Designed scenario

Solar optimized design scenario

Fig. 6. Two different scenarios are investigated: design scenario and solar optimized design starting from current scenario.

The main aim of this analysis was to evaluate if the optimization of the volume improves the solar access, increasing the available solar radiation on the façade of every building. The results in Fig. 7 show that the solar radiation on the building envelope increases in every building of the compound.

In particular the optimization has been done for couples of buildings at a time, in order to reduce the effect of reciprocal shading.

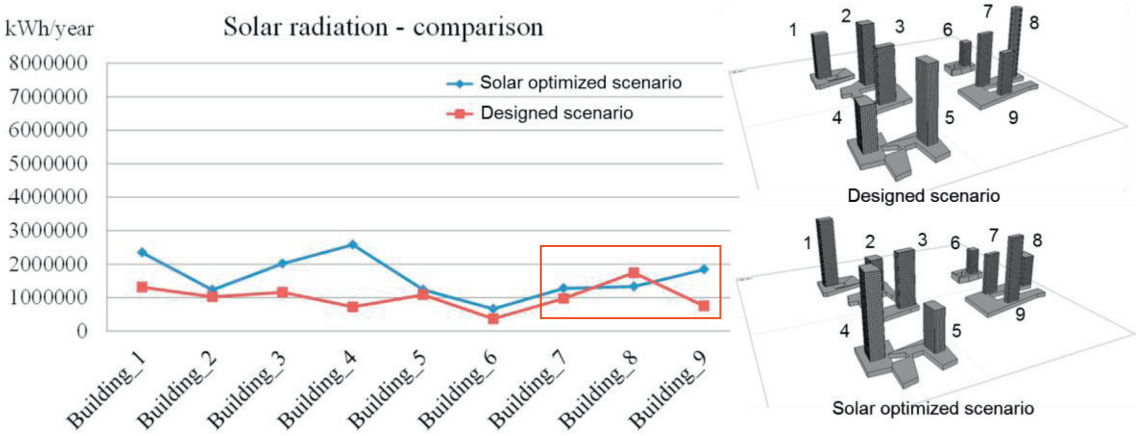


Fig. 7. Results of the direct solar radiation for designed scenario and solar optimized scenario with ambient bounces equal to 0 and ground reflectance equal to 0.0%

It is necessary to underline that the analyses were performed considering all the new buildings as isolated volumes. This aspect guarantees the lack of the overshadowing due to the context, but not the mutual influence among the different buildings of the district.

Table 4. Results, considering only the direct solar radiation in designed scenario and solar optimized design scenario

	Conditions	Designed scenario		Solar optimized design scenario		Results
Building	Ambient bounces (ab) and ground reflectance (Gr. refl. [%])	Direct solar rad. (kWh/year)	(kWh/m^{2}year)	Direct solar rad. (kWh/year)	(kWh/m^{2}year)	Increment or decrement [%]
Building_1	ab=0, Gr=0,0	1,310,364	213	2,345,411	334	44%
Building_2	ab=0, Gr=0,0	1,023,747	143	1,231,154	311	17%
Building_3	ab=0, Gr=0,0	1,160,552	199	2,013,512	345	42%
Building_4	ab=0, Gr=0,0	719,987	160	2,579,154	319	72%
Building_5	ab=0, Gr=0,0	1,082,529	149	1,232,091	311	12%
Building_6	ab=0, Gr=0,0	366,701	172	659,899	323	44%
Building_7	ab=0, Gr=0,0	972,523	208	1,276,659	357	24%
Building_8	ab=0, Gr=0,0	1,741,104	310	1,329,160	315	-31%
Building_9	ab=0, Gr=0,0	748,828	206	1,838,254	334	59%
Total	ab=0, Gr=0,0	9,126,335	1,760	14,505,296	2949	37%

The values within the red rectangle in Fig. 7 and Table 4 underline the specific configuration for buildings 7, 8 and 9, which have been optimized considering two buildings at a time. However, results demonstrate that in this case the optimization is not as efficient as in others, because three buildings were considered simultaneously. The relationship among three or more buildings is obviously more complex than between a couple of buildings and should be calculated with more sophisticated analyses. Results are presented in Table 4.

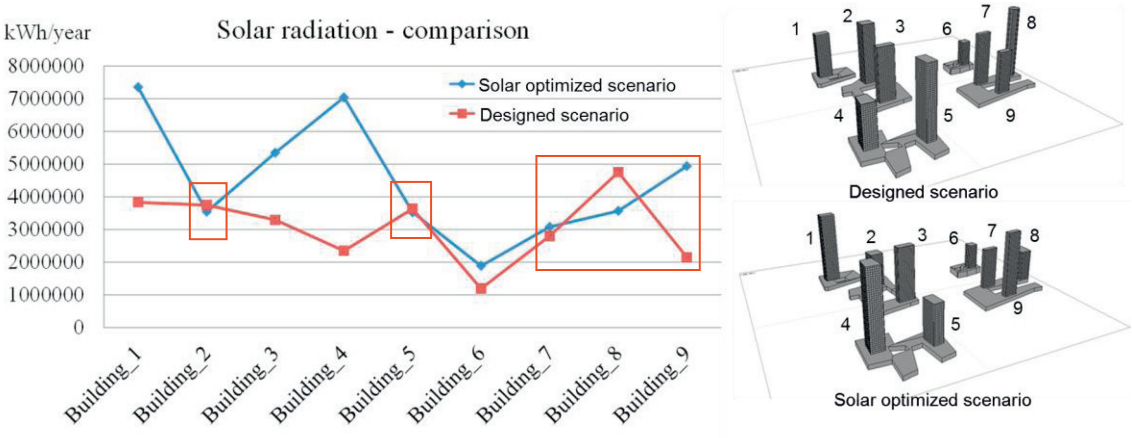


Fig. 8. Results of all contribution of solar radiation for the designed scenario and solar optimized design scenario with ambient bounces equal to 3 and ground reflectance equal to 15%

The second analysis is conducted on all buildings in both scenarios, setting the raytrace conditions to values of 3 for ambient bounces and 15% for the ground reflectance.

The aim of this analysis was to confirm the results of the first simulation with different raytrace parameters, considering the mutual interaction among buildings and the solar reflections on each other.

Table 5. Results considering all contribution of solar radiation in designed scenario and solar optimized design scenario

	Conditions	Designed scenario		Solar optimized design scenario		Results
Building	Ambient bounces (ab) and ground reflectance (Gr. refl. [%])	Global solar rad. (kWh/year)	(kWh/m^{2}year)	Global solar rad. (kWh/year)	(kWh/m^{2}year)	Increment or decrement [%]
Building_1	ab=3, Gr=0,15	3,830,655	616	7,353,787	926	48%
Building_2	ab=3, Gr=0,15	3,744,028	523	3,541,690	894	-6%
Building_3	ab=3, Gr=0,15	3,290,385	564	5,348,066	917	38%
Building_4	ab=3, Gr=0,15	2,344,903	520	7,040,202	871	67%
Building_5	ab=3, Gr=0,15	3,633,246	501	3,529,665	892	-3%
Building_6	ab=3, Gr=0,15	1,190,870	558	1,884,143	884	37%
Building_7	ab=3, Gr=0,15	2,798,506	597	3,077,191	862	9%
Building_8	ab=3, Gr=0,15	4,752,258	846	3,567,626	864	-33%
Building_9	ab=3, Gr=0,15	2,144,541	591	4,938,909	898	57%
Total	ab=3, Gr=0,15	27,729,391	5,317	40,281,278	8,008	31%

All buildings, except number 1, lost part of the solar radiation increment due to the effects of overshadowing by the neighbouring buildings. Only building 1 achieved an increment of solar radiation due to reflections. Furthermore, it is fair to underline three situations where the increments of the first analysis decreased until they assumed negative values (building number 2 and 5). Solar radiation available on the group of three buildings (7, 8 and 9) is worse than the one in the first analysis. Finally, considering the global solar radiation the increment is about 31%. Results are summarized in Table 5.

The last analysis is conducted with the same raytrace parameters than the previous simulation, but considering the volumes of the new buildings within the existing context. The aim of this simulation is to calculate the overshadowing and solar reflection effects on the façades of the buildings, in terms of increment or decrement of the available solar radiation, caused by the neighbouring existing buildings.

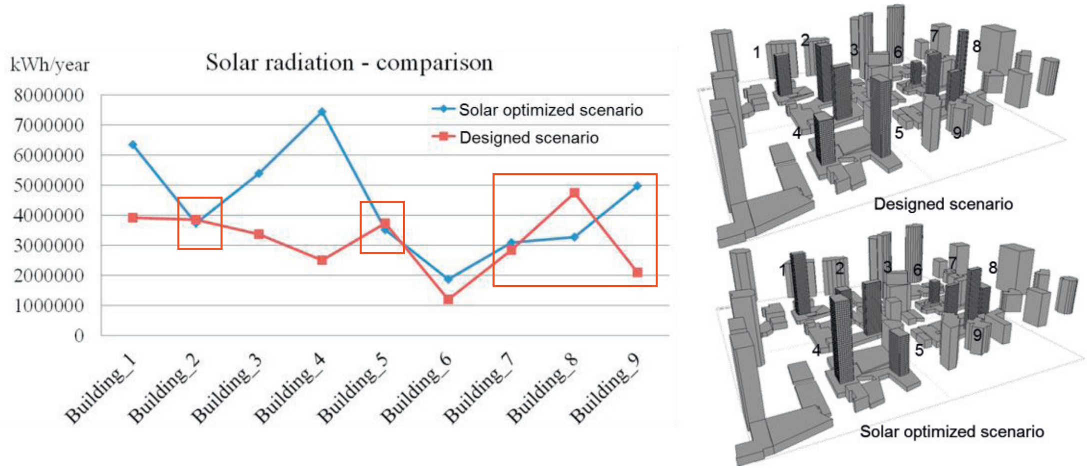


Fig. 9. Results of all contribution solar radiation for the designed scenario and solar optimized design scenario in existing context with ambient bounces equal to 3 and ground reflectance equal to 15%

Table 6. Results considering all contribution of solar radiation in designed scenario and solar optimized design scenario within context

	Conditions	Designed scenario		Solar optimized design scenario		Results
Building	Ambient bounces (ab) and ground reflectance (Gr. refl. [%])	Global solar rad. (kWh/year)	(kWh/m^{2}year)	Global solar rad. (kWh/year)	(kWh/m^{2}year)	Increment or decrement [%]
Building_1	ab=3, Gr=0,15	3,915,044	630	6,343,403	902	38%
Building_2	ab=3, Gr=0,15	3,851,539	538	3,730,433	942	-3%
Building_3	ab=3, Gr=0,15	3,365,208	577	5,388,376	924	38%
Building_4	ab=3, Gr=0,15	2,503,552	555	7,442,971	921	66%
Building_5	ab=3, Gr=0,15	3,731,127	515	3,514,016	888	-6%
Building_6	ab=3, Gr=0,15	1,194,520	560	1,866,805	876	36%
Building_7	ab=3, Gr=0,15	2,839,061	606	3,086,986	864	8%
Building_8	ab=3, Gr=0,15	4,741,891	844	3,270,032	792	-45%
Building_9	ab=3, Gr=0,15	2,091,513	577	4,971,688	904	58%
Total	ab=3, Gr=0,15	28,233,456	5,401	39,614,710	8,013	29%

Results are very close to the previous ones, although the overshadowing effect, caused by the neighbouring existing buildings, have some influence on the solar availability. In fact only for three buildings (buildings 2, 7 and

9) the value of global solar radiation on the façades is increased, although the increments are not very high. On the contrary, the decrements due to the overshadowing effect are substantial, especially for building number 1, which loses 10% of the global solar radiation. Results are collected in Table 6.

5. Conclusion

The simulation conducted with Daysim, considering all of the new building volumes in both scenarios, demonstrated that the increments of direct solar radiation (Fig. 7) are positive when comparing the solar optimized scenario to the original one, for every building except for building 8, as a result of a partial optimization of three buildings (buildings 7, 8 and 9). This explains that the tool works well if two buildings are considered, while the optimization of three or more buildings required more refined analyses. The differences among values increase when considering the effects of overshadowing and solar reflections from other buildings (Fig. 8), with increments or decrements of global solar radiation values. These effects increase if the analysis is done in the context (Fig. 9).

It is important to underline that the analyses have been conducted assigning only concrete plaster as finishing material for all façades, with its specific solar reflection. It is reasonable to guess that using other materials with different reflection values, the increments or decrements of global solar radiation available on the façade would increase or decrease. Further studies to analyse the effects of other materials or by using the same material with different RGB reflection values will be a part of the future work.

The development of this study will include the evaluation of the façade areas where solar radiation is higher thanks to direct radiation and to reflection from nearby buildings. This will identify areas with more potential for solar exploitation using photovoltaic or solar thermal panels installed on the façades. The amount of energy that could be produced under different boundary conditions will be evaluated as well, together with payback periods of investments.

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