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District geometry simulation: a study for the optimization of solar façades in urban canopy layers

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Abstract

This paper shows the results of a research aimed at assessing the amount of energy that can be produced by solar envelopes (facades and roofs) in urban contexts.
A preliminary set of simulations was carried out, through dynamic yearly analyses on a sample building, to identify the main parameters influencing the availability of solar radiation and to optimize the building's shape. The general target is to maximise solar radiation available on the external building envelope, in order to exploit it through building integrated solar systems.
Furthermore, the effect of reflected solar radiation has been analysed by simulating different finishing materials (green façades, glazed façades, concrete façades and aluminium façades) on the neighbouring buildings.

Keywords: Solar radiation; solar façades; Solar potential; Solar reflection

1. Introduction

The built environment accounts for over 40% of the world's total primary energy use and for 24% of greenhouse gas emissions [1]. With the aim of reducing the energy consumption of buildings and the related environmental impact, several regulations and demonstration activities are pushing for the adoption of the "net zero energy" standard. Among these regulations, the European Directive on the energy performance of buildings (2010/31/EU), requiring that new buildings comply with the "nearly

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zero energy" standard by 2020, is probably the one with the largest potential impact, as it regards all of the 27 Member States of the European Union.

Although the standard definition of a nearly zero energy building is still under discussion [2], the spirit of the Directive is about matching a very limited energy need of the building with the amount of energy that can be sourced on (or near) the site. Some existing buildings prove the feasibility of scenarios where the energy used for heating and cooling is offset by the yearly production of renewable solar energy [3]. However, these prototypes are generally isolated, low-rise buildings with optimal solar exposure, while most of the world's population live in dense urban areas [4], and in Europe, policies promote increasing density in existing urban areas to reduce sprawl [5]. This means that most of the buildings will have to aim for the nearly zero energy standard in a context where the orientation, availability of surfaces exposed to the sun and the overshadowing conditions can be far from optimal.

In view of the European 2020 requirements, it is then interesting to assess the solar potential of buildings located in urban areas, where the availability of solar radiation on the building envelope depends also on the shading conditions and on the reflections from nearby surfaces. On the other hand, it should not be underestimated that a higher amount of solar radiation on facades and roofs means higher cooling loads in summer and increased surface temperatures. The latter can have an impact on the air circulation and the temperature distribution within urban canyons, leading to high summertime outdoor air temperatures (Urban Heat Island effect – UHI) that increase cooling-energy use and accelerate the formation of urban smog [6].

2. Material and method

Within this scenario, the general aims of the work are to demonstrate the influence that building and façade design have on the total amount of solar radiation incident on the external building envelope and to increase the energy production of integrated solar systems by optimizing the shape of the buildings in the district morphology. Distribution of volumes, road pattern and building orientation, finishing materials, street width and relative buildings height are all parameters that could potentially affect solar rays' access on buildings. These aspects could also have a strong influence on general and local climatic variations (mitigation of urban heat island effect), as well as on users comfort, both indoors and outdoors.

In particular, this paper presents a parametric study on the optimization of the building's volume and the numerical evaluation of the solar radiation insisting on the building envelope, in order to assess if facades can be exploited, in parallel with the roof, for energy production in dense urban areas, where there may be significant overshadowing caused by existing constructions. The analysis of basic models allows assessing energy need and calculating potential energy production under different design conditions (height and size of buildings, distance between blocks, cladding materials, etc.).

3. Theory and calculation

3.1. *Type of analyses and aims*

The specific aims of this study are:

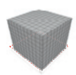
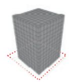
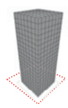
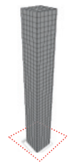
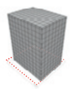
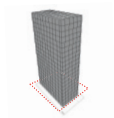
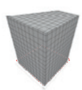
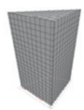
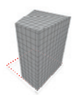
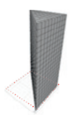
- optimization of the building shape with respect to solar access, keeping the volume constant;
- organization of the building volume in order to maximize solar exposure;
- evaluation of the solar potential of the building, considering the influence of solar reflection of the external surfaces of the neighbouring buildings, in different scenarios of painting colours and finishing materials;
- qualitative analysis of the impact of radiative properties of surfaces on urban heat island effect (mean radiant temperature increase).

In particular, the availability of solar radiation on the building façades has been mainly considered, while the roof has been calculated separately. The reasons for this choice are that for tall buildings, the amount of roof space per apartment floor area is relatively limited and the roof surface has often to be shared among different concurrent functions (services, shafts, terraces, etc.) that limit the potential for the installation of solar panels; because of this, is thus possible to cover just a limited portion of the energy demand of the building. In dense urban conditions, then, it may be sensible to explore the potential of other exposed surfaces, such as façades, although their orientation and tilt are not optimal for solar energy production over the year.

Simulations have been carried out in two different steps: in the first part, the global annual radiation on the building envelopes of simple volumes has been estimated; in the second part the analysed volume has been included into a hypothetical district consisting of nine blocks about 1000 m^3 each. All the simulations have been carried out for the city of Milan – Italy (latitude 45.27° N, longitude 9.11° E) using statistical data recorded at the Milan Malpensa airport (source: EnergyPlus weather data website).

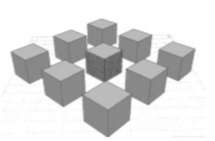
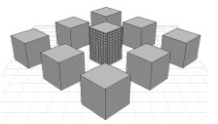
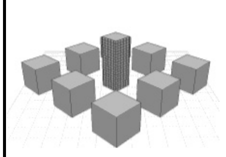
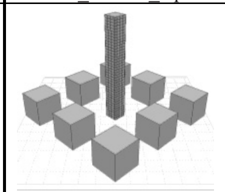
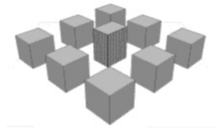
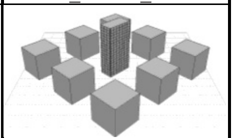
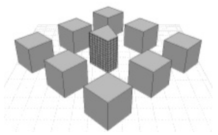
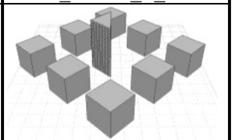
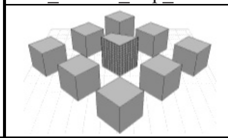
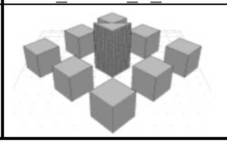
The first analyses (irradiance variation due to shadowing) have been conducted on a constant volume of 1000 m^3, varying the covering ratio of the development (S_c, i.e. the ratio between the building's footprint and the area of the lot) between 100% and 25%. Different footprints (square, rectangular, trapezoidal and triangular shapes) and different heights (in the range between 10 and 40 m) have been simulated. Orientation and shapes of the building plan have been selected in order to minimize the north façade surface and to guarantee a minimum ratio between two adjacent sides of at least 1:2, as shown in Table 1.

Table 1. Buildings simulated in analysis 1: different footprints, covering ratios (S_c) and building height (H), keeping the building's volume constant

Shape / **S_c & H**	**100% - H=10 m**	**75% - H=13.3 m**	**50% - H=20 m**	**25% - H=40m**
Square	100_NS_sq 100_NWSE_sq	75_NS_sq 75_NWSE_sq	50_NS_sq 50_NWSE_sq	25_NS_sq 25_NWSE_sq
				
Rectangle		75_NS_rect 75_NWSE_rect	50_NS_rect 50_NWSE_rect	
				
Trapezium **Triangle**		75_NS_trap_NE 75_NWSE_trap_NE	50_NS_tr_NE 50_NWSE_tr_NE	
				
		75_NS_trap_NW 75_NWSE_trap_NW	50_NS_tr_NW 50_NWSE_tr_NW	
				

Afterwards, the reference building has been included into a simple district composed of nine blocks, 1000 m^3 (10x10x10 m) each (Table 2). As in the previous set of simulations, the variations of covering ratio, as well as the changing of shape and height of the reference building have been simulated, maintaining constant the building's total volume. Reflection of energy from nearby surfaces has been taken into account under different hypotheses: the reflectance properties of surrounding envelope surfaces have been modified according to several assumed claddings (plaster with different colours from black to white, aluminium facade, concrete facade, glass facade and green facade).

Table 2. Analysis 2: simulated buildings into hypothetical districts consisting of nine blocks of about 1000 m^3 each

Shape / **S_C & H**	**100% - H=10m**	**75% - H=13.3 m**	**50% - H=20m**	**25% - H=40m**
Square	100_NS_sq 100_NWSE_sq	75_NS_sq 75_NWSE_sq	50_NS_sq 50_NWSE_sq	25_NS_sq 25_NWSE_sq
				
Rectangle		75_NS_rect 75_NWSE_rect	50_NS_rect 50_NWSE_rect	
				
Trapezium **Triangle**		75_NS_trap_NE 75_NWSE_trap_NE	50_NS_tr_NE 50_NWSE_tr_NE	
				
		75_NS_trap_NW 75_NWSE_trap_NW	50_NS_tr_NW 50_NWSE_tr_NW	
				

All the simulations have been performed with the program Daysim (version 3.1 b), 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 Autodesk Ecotect Analysis 2011 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. At the end of the solving procedure, the rather large resulting files have been managed with Matlab algorithm.

Daysim is a validated Radiance-based program [7], developed and validated for daylight calculations of complex transparent systems [8], that combines a backward-ray-tracing algorithm, a daylight coefficient approach and the Perez Sky Model to simulate time series of solar irradiances. Two simulation methods are allowed: the “DS” method and a revised method added in 2008, denominated “DDS –s” standard daylight coefficient model with overshadowing [9]. Both daylight coefficient methods differ in how direct and diffuse irradiances are treated. DDS allows for a more detailed analysis of direct solar contributions while sacrificing time and computing resources [10].

Table 3. Set of “rtrace” parameters used for all radiance-based simulations

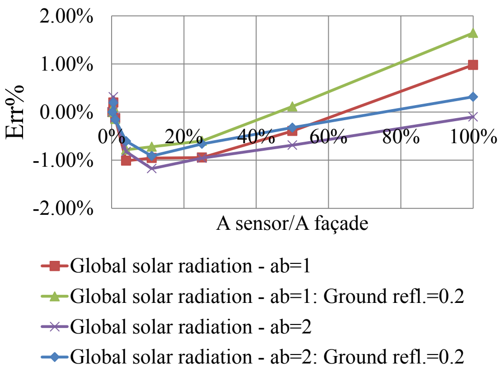
ambient bounces	ambient division	ambient super-sample	ambient resolution	ambient accuracy	specular threshold	direct sampling	direct relays
1 – 3	1000	20	300	0.1	0.15	0.20	2

Table 3 details the final parameters for all Radiance-based simulations developed in the first and second part of the study. The set of “rtrace” parameters has been simplified with respect to the parameters used in previous works concerning the simulations of solar availability [10]: this choice has been taken after demonstrating that this simplification does not affect the final results.

“Ambient bounces (ab)” is the variable parameter in the simulations: it represents the maximum number of diffuse bounces computed by indirect calculations. While in the first part of the analyses an ab equal to 1 and a ground reflectance of 0 have been used in order to consider only the effect of global sky solar radiation, in the second part of the analyses a ground reflectance of 0.15 (corresponding to a weathered asphalt) and an ab equal to 3 have been used for computing multiple solar reflections between the main and the neighbouring buildings.

Each set of simulation has been run with different orientation, so as to consider the solar exposure of the buildings façades, with respect to the directions of the roads: the solar radiation values have been calculated in North – South (NS), and North - West, South - East (NWSE) orientations.

3.2. *Sensitivity analysis*



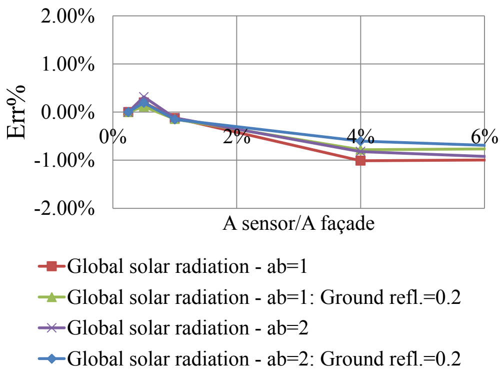


Fig. 1. (a) Results of the sensitivity analysis with different simulation conditions and accuracy of the sensors distribution; (b) Enlargement of the sensitivity analysis (A_{sensor}/A_{facade} < 6%)

A sensitivity analysis has been carried out in order to define the sensors’ distribution on the building envelope: it is thus possible to assess how the increase of resolution settings affects the accuracy of simulation results. This analysis has been done on the base case (100_NS_Sq) with different sensors distribution and hence different areas of influence.

Fig.1 shows the results of the sensitivity analysis: the error (Err%), calculated as the deviation between the solar radiation calculated on each grid and the one obtained on a reference grid of 400 sensors, is displayed as a function of grid size (A_{sensor} / A_{facade}). As evident from Fig.1 (b), a grid composed of 100 sensors (A_{sensor}/A_{facade} = 1.0%) has an acceptable error of 0.15% and a convergence speed higher than the one related to finer grids. (i.e. 200 and 400 sensors) and thus has been chosen for the further analyses.

4. Results and discussion

4.1. *Simulation of a single building (solar exposure)*

The first set of simulations has been carried out on a single building with four different values of covering ratio S_c: 100%, 75%, 50% and 25% and keeping constant the building's volume to 1000 m^3. The results of the simulations, expressed in term of global radiation (kWh/year), are summarized in the column graphs of Fig. 2. In order to split the global amount of solar radiation on building envelope, contributions of vertical surfaces and of roofs are shown in the graphs. In this way different footprints are easily comparable. On the NS orientation, the 50_NS_Tr_NE (triangular footprint with 50% of covering ratio and NS orientation) has the highest global radiation, equal to 410,937 kWh/year (561 kWh/m^{2}year), sum of 358,427 kWh/year on the facades and of 52,510 kWh/year on the roof. If only the facade's contribution is considered, the highest value of annual solar radiation (382,196 kWh/year) is obtained for the building 25_NS_Sq (square footprint with 25% of covering ratio).

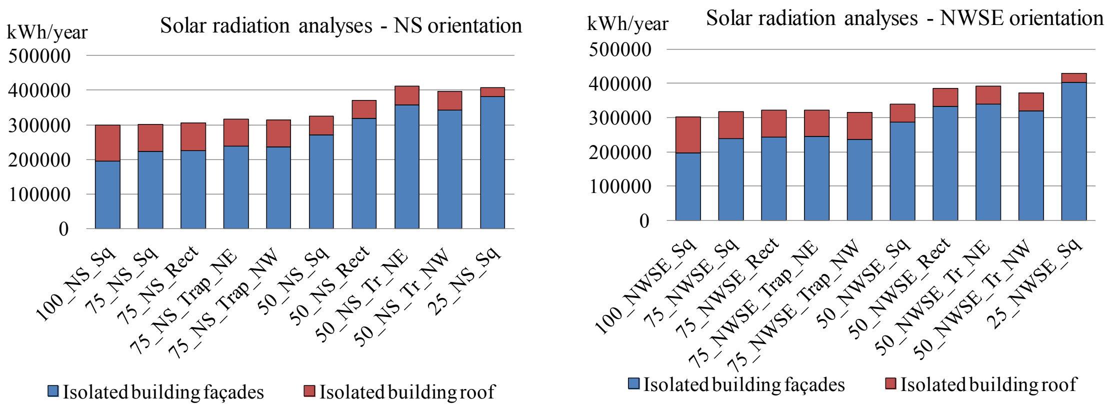


Fig. 2. (a) solar radiation analyses for different configurations of the volumes for NS orientation: (b) and NWSE orientation

On the NWSE orientation the building 25_NWSE_Sq (square footprint with 25% of covering ratio) has the highest global solar radiation incidence (429,902 kWh/year or 521 kWh/m^{2}year), and also the highest incidence of solar radiation on vertical surfaces (403,647 kWh/year).

It is furthermore noticeable how, on an isolated building, the decrease of S_c is highly beneficial for the increase of global incident solar radiation (for both the two exposures NS and NWSE): an increase of about 40% of global solar radiation incident on the building's envelope is obtained, mainly due to the increase of total exposed surface. Finally, it can be noticed how, keeping S_c constant, the most beneficial solutions are the ones for which the total surface exposed to SE/SW is maximized (triangular and trapezoidal versus rectangular and square).

4.2. *Simulation of the building in a district (solar access).*

In the second part of the study, a parametric analysis on the reference building included in a simple district composed of nine buildings (1000 m^3 each) has been performed.

All simulations have been carried out in two different scenarios, in order to calculate the different contributions of solar shadings and of indirect solar radiation reflected by neighbouring buildings. Four external cladding materials (green, glazing, concrete plaster and aluminium) have been simulated (Table 4). For the concrete plaster material, six different colours have been simulated, with reflectance values variable within the range 0.0% to 100%. The extreme values 0% and 100%, respectively for an ideally totally black and ideally totally white facade, have been considered only as maximum and minimum reference values.

Table 4. List of Radiance materials properties

material	Radiance material description	Number of values	R reflectance	G reflectance	B reflectance	Specularity	Roughness
Conc plaster 0% R	void plastic	0 0 5	0.000	0.000	0.000	0.00	0.00
Conc plaster 30% R	void plastic	0 0 5	0.296	0.296	0.296	0.00	0.00
Conc plaster 55% R	void plastic	0 0 5	0.549	0.549	0.549	0.00	0.00
Conc plaster 60% R	void plastic	0 0 5	0.596	0.596	0.596	0.00	0.00
Conc plaster 90% R	void plastic	0 0 5	0.890	0.890	0.890	0.00	0.00
Conc plaster100%R	void plastic	0 0 5	1.000	1.000	1.000	0.00	0.00
green facade	void plastic	0 0 5	0.150	0.600	0.200	0.00	0.00
concrete facade	void plastic	0 0 5	0.549	0.549	0.549	0.00	0.00
aluminum facade	void plastic	0 0 5	0.900	0.880	0.880	0.80	0.20
glazed façade	void glass	0 0 3	0.750	0.820	0.820	/	/

The results of the analyses have been compared to reference case (NS_100_Sq for the NS orientation and NWSE_100_Sq for the NWSE orientation): the percentages of variation of global solar radiation on vertical surfaces are collected in Table 5 and Table 6.

Table 5. Parametric analysis of solar access on buildings in a district NS oriented

Analysis Shape	0.0% Refl.	30% Refl.	55% Refl.	60% Refl.	80% Refl.	100% Refl.	Green façades	Glazed façades	Concrete plaster façades	Alum. façades
100_NS_Sq	-17%	-9%	-1%	0%	7%	14%	-13%	-9%	-1%	9%
75_NS_Sq	5%	14%	21%	23%	32%	36%	9%	15%	21%	28%
75_NS_Rect	7%	15%	23%	24%	34%	38%	11%	14%	23%	30%
75_NS_Trap_NE	10%	18%	26%	27%	37%	41%	14%	17%	26%	34%
75_NS_Trap_NW	9%	17%	25%	27%	37%	41%	13%	16%	25%	33%
50_NS_Sq	40%	48%	55%	57%	66%	70%	44%	47%	55%	61%
50_NS_Rect	50%	57%	66%	67%	77%	81%	54%	57%	66%	72%
50_NS_Tr_NE	69%	78%	87%	89%	100%	104%	74%	78%	87%	94%
50_NS_Tr_NW	68%	77%	85%	87%	98%	102%	72%	76%	85%	92%
25_NS_Sq	116%	122%	128%	129%	137%	140%	119%	121%	128%	131%

Table 6. Parametric analysis of solar access on buildings in a district NWSE oriented

Analysis Shape	0.0% Refl.	30% Refl.	55% Refl.	60% Refl.	80% Refl.	100% Refl.	Green façades	Glazed façades	Concrete plaster façades	Alum. façades
100_NWSE_Sq	-18%	-10%	-2%	0%	9%	13%	-14%	-7%	-2%	9%
75_ NWSE_Sq	5%	13%	20%	22%	31%	35%	9%	14%	20%	28%
75_ NWSE_Rect	5%	13%	21%	23%	32%	36%	9%	15%	21%	29%
75_NWSE_Trap_E	9%	18%	26%	27%	37%	41%	14%	17%	26%	33%
75_NWSE_Trap_W	8%	16%	24%	27%	35%	40%	12%	15%	24%	32%
50_NWSE_Sq	39%	47%	54%	55%	65%	69%	43%	47%	54%	60%
50_NWSE_Rect	61%	69%	77%	78%	88%	92%	65%	69%	77%	83%
50_NWSE_Tr_NE	68%	77%	86%	88%	99%	103%	73%	77%	86%	92%
50_NWSE_Tr_NW	64%	73%	82%	84%	95%	99%	68%	72%	82%	89%
25_NWSE_Sq	114%	120%	126%	127%	134%	137%	117%	119%	126%	129%

The results show that the effect of the shadowing by neighbouring buildings produces a decrease of the global solar radiation reaching the reference building facade of about 17% (100_NS_Sq 0.0% on Table 5 and Table 6). Furthermore the shadowing effect reduces the yearly global radiation on the most exposed facade of about 27%.

The shadowing effect is generally balanced by the diffuse solar radiation reflected by neighbouring buildings: for the base case (square footprint with 100% of covering ratio), neighbouring cladding materials with more than 60% of reflectance are able to totally compensate the solar energy losses due to the shadows.

Also the building shape is greatly affecting the total amount of solar radiation incident on facades. As for the isolated building, the increase of building height tends to increase the global amount of solar radiation on vertical envelope, but the effects of reflections from neighbouring buildings are reduced with a reduction of covering ratio. Extracting, for example, from Table 5 the results for the square footprint (100_NS_Sq, 75_NS_Sq, 50_NS_Sq and 25_NS_Sq), is evident that the increase of global solar radiation on vertical envelopes due to reflections is reduced from a global 26% for S_c = 100% to a global 15.2% for S_c = 25%.

Furthermore also the footprint shape has an impact on global solar access on buildings: generally for both covering ratios of 75% and 50%, trapezoidal/triangular footprints are more beneficial than the square/rectangular ones, due to the increase of the facade area most exposed to solar radiation (SE and SW orientations).

Comparing, instead, Table 5 and Table 6, it can be recognized that the orientation is only minimally affecting the global annual amount of solar radiation on vertical surfaces (less than 2% of decrease for a 45° rotation of the district orientation).

In Fig.3 the distribution of global annual solar radiation on the most exposed facade is shown. In these simulations, concrete facades have been used, as well as different footprints (square, rectangular, trapezoidal and triangular) and covering ratios (100%, 75%, 50% and 25%) have been compared for a district perfectly north-south oriented. It is noticeable how the increase of facade's height is highly beneficial, increasing the maximum value of global specific solar radiation. Due to the effect of reflected component, the facade strip between 15 m and 30 m has the maximum amount of global solar radiation: this is evident looking at the elevation of 25_sq south facade.

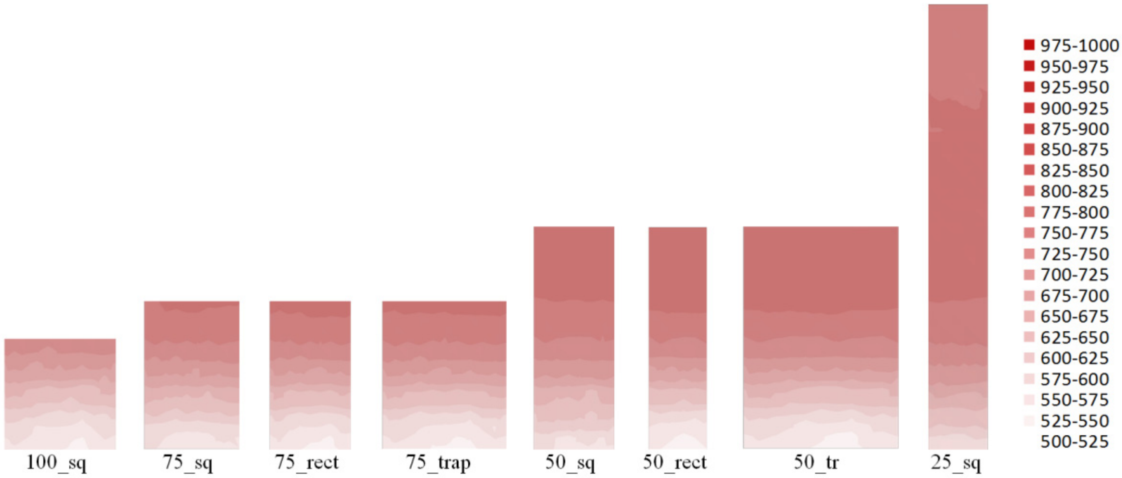


Fig. 3. Concrete facades: distribution of global annual solar radiation on the South-exposed facade (values expressed in kWh/m^{2}y)

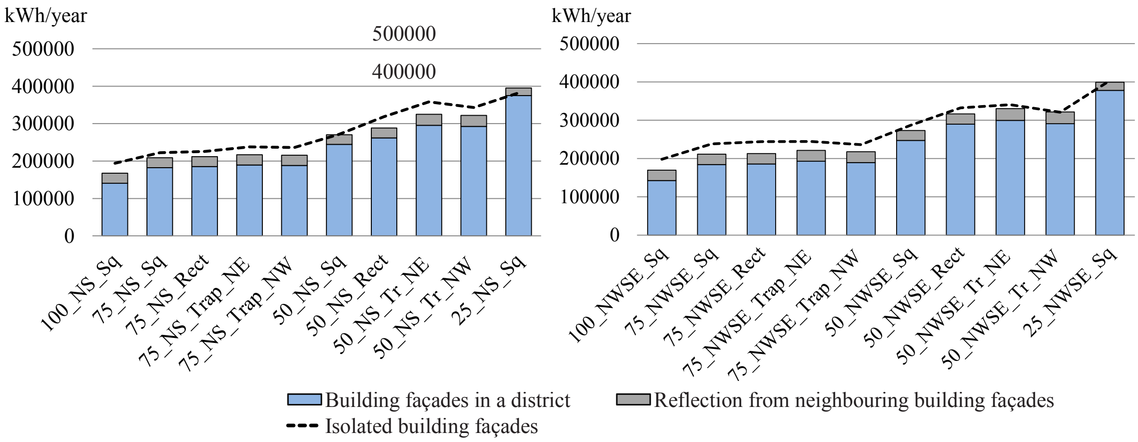


Fig. 4. Concrete facades. Global and reflected solar radiation components as a function of building's footprint. (a) NS oriented district; (b) NWSE oriented district

In Fig. 4, global solar radiation on vertical surfaces of each building's shape within the ideal district is compared with the equivalent value on the isolated building's envelope. Due to the lower percentage of facade's surface that is directly shaded, only the 25% covered square footprint is not considerably affected by surrounding buildings: in this case the reflected solar components totally compensate the energy losses due to solar shading.

5. Conclusion

The study has shown for different covering ratios and building footprints, how the distribution of the volume is able to maximize the solar radiation on building envelope, pointing out the importance of building façades, in terms of solar potential and energy production.

Different cladding materials have been simulated in order to consider the beneficial effects on total solar energy due to reflections. Some general considerations can be drawn.

- If the building's volume is kept constant, the solar exposure, as well as the solar access to building's façade is greatly affected by building shape: the relative increase of total annual solar radiation on vertical surfaces, changing building's covering ratio from 100% to 25%, is up to 95% for isolated buildings and up to 138% for surrounded buildings.
- The component of solar radiation reflected by surrounding buildings, globally on all the exposed facades, is able to compensate the losses due to shadowing if light colours are provided (with solar reflectance higher than 60%).
- Highly reflective materials beneficially increase reflected solar radiation, but visual and thermal comfort assessment has to be carried out: local increases of solar radiation on building's envelopes (as the ones obtained in the strip between 15 m and 30 m in the 25% covered square footprint building) could cause overheating and glare effects, especially if the building has wide and unshaded windows.
- Dark surfaces of surrounding buildings are not only reducing the solar access on reference building (due to the minimal amount of reflected solar component) but are also potentially increasing the UHI effect due to the increase of air and superficial temperatures. A good solution able to mitigate the UHI effects is the green facade, even if for the general aim of this study its contribution is limited.

Still open issues are referred to the reduction of solar access of surrounding buildings due to the shape modification of the reference building and to the relationship of solar access requisite with other urban environmental issues (increase of cross ventilation due to the Urban Canyon effect caused by the modification of the ratio between building's heights and distances, reduction of facade's superficial temperatures, solar access of surrounding buildings).

Next steps of this study will answer to these issues as well as will consider the complex transformation of volume and building's footprint with the aid of parametric softwares manipulating geometrical transformations (Grasshopper for Rhyno, Galapagos and Geco plug-in).

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