A STEP TOWARD THE GLOBAL ASSESSMENT OF DISTRICT PROJECTS: SOLAR INDICATORS AND WAY TO QUANTIFY THEM

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ABSTRACT

This paper deals with solar indicators and simulation as a step toward global assessment of a district. The final aim is to assess district projects as much exhaustively as possible, including among other things energy aspects, acoustic aspects, emissions… The present article deals only with solar aspects. First are presented the key indicators regarding solar aspects. Next, solar simulations are run at the scale of the district with the SOLENE software. Important parameters such as the time span and the reflectance of surface are investigated: the simulations demonstrate that reflections must be taken into account even at early stage of design. Concerning the time span, shading effect has a significant influence in dense districts and prevents from using a single day to represent the solar behavior during a month or a season.

INTRODUCTION

A French project named ADEQUA aims to develop a toolbox to assist in the planning of urban operation. This methodology allows actors in the building sector to define and to qualify indicators related to sustainable development and also to consider different sustainable alternatives for a project. Urban planning can be treated at different scales: the building, the district, the city, the territory… The district has been chosen as it seems to be the best adapted to sustainable development assessment and to urban planning (Cherqui et al., 2004). Starting from the global objectives, quantification or qualification of indicators will lead to the evaluation of different alternatives of a district using multicriteria analysis. This method is a design method allowing solutions to be compared in order to find the best adapted or rather the least bad.

The core of the methodology is the set of indicators allowing assessing different project's alternatives. They need to be better defined and recent research focused on their use (Khanna, 2000; Kurtz et al., 2001; Mendoza et al., 2004; Shi et al., 2004). Kurtz et al. (2001) defined indicator as "a sign or signal that relay a complex message, from potentially numerous sources, in a simple and useful manner". Indicators are also a mean to highlight key parameters to be taken into account during design stage. Assessment of indicators involves the use of computer tools for predicting energy consumption, sunshine, acoustic levels, etc. This paper deals only with solar indicators and solar simulation as a step toward the global assessment of a district. "The huge solar resource available within cities is not exploited. One reason for this is that city planners have no tools to help them make informed decisions on how best to deploy solar energy technology" (Gadsden et al., 2003).

The following section presents the key indicators regarding solar aspects, which have been produced by the literature. Next, solar simulations are run at the scale of the district with the SOLENE software. Important parameters such as time span and reflectance of surface are investigated. Results are then discussed and conclusions are drawn.

SOLAR INDICATORS

Introduction

In the following, a state-of-the-art of the most pertinent indicators is presented. Each indicator is introduced to quantify a precise criterion of a project. Yet, indicator will be given without an average value or an optimum value, as it is strongly dependant of many parameters such as geographical location, objectives, specific climate, vernacular specificities… Other pertinent indicators which deserve to be mentioned in this paper may have not been found in the lavish literature and authors will be glad to have information upon them.

Solar irradiance and illuminance

Solar irradiance and illuminance on a surface are the most often used and numerous variations exist. These indicators give elementary information of solar power density [W/m²] and luminous power density [lux] received by a surface. "Knowledge of direct irradiance is important in applications where the solar radiation is concentrated..." (Lopez et al., 2005). Moreover "effective daylighting can reduce electricity use, not only for artificial lighting but also for air-conditioning in hot climates, due to less heat dissipation from electric lighting fittings" (Li et al., 2005). Both of these indicators are widely used to evaluate possibility of passive and/or active solar systems.

The computation of irradiation value can be done for different time steps (an hour, a day, a season, a year…), depending on the aim. Compagnon (2004) utilizes the total annual irradiation or illuminance aggregated into cumulative distribution in order to provide an overall view of the solar and daylight availability (see Figure 1).

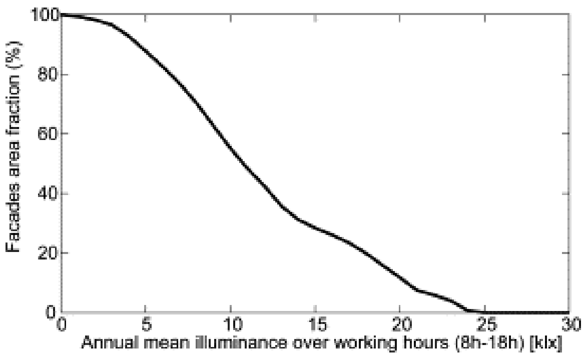

Figure 1 : Cumulative distribution of mean annual illuminance (Compagnon, 2004)

The distribution presents the percentage of façades lit for each annual irradiation or illuminance values.

An average value for the whole district can also be used: different projects are then compared upon their exposure to sun. Hot and arid climate will involve the search for a low average value instead of cold climate which seek a high value. Yet this average value enables only to compare different projects but not different districts in different locations, because the irradiance and illuminance values are strongly dependant of location. In this case, irradiance level and illuminance level are useful to provide normalized values which can be compared.

Repartition maps

Irradiation level repartition can be defined as the percentage of the maximum value of the area studied H_L (equation 1), and represented on a spatial repartition map:

$$H_{Li}[\%] = \frac{H_i}{\max(H_j|j)} \qquad (1)$$

Figure 2 shows an example of an irradiation level distribution on a district. Spatial indicators give information on "hot spot" where the flux is maximum and permit to control if solar flux is distributed wisely, e.g. on glazed surface for daylight, on roof for photovoltaic cells or for solar thermal energy…

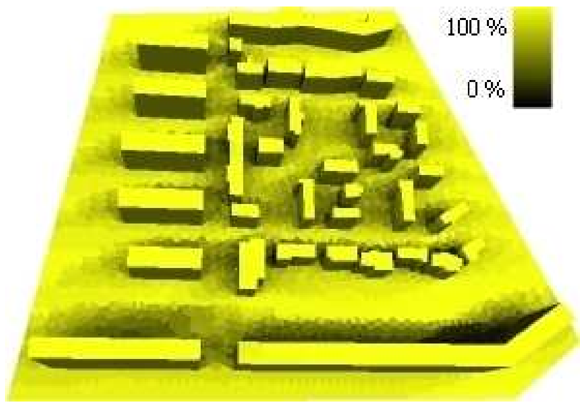

Figure 2 : spatial distribution of the total direct solar irradiation (H_L) from the 1st to the 4th of june

Potential level of a surface i can be defined as a potential irradiation (H_{Pi}) compared to the theoretical maximum value. The theoretical maximum value is the irradiation of the same surface but with no shading effect from other building (unobstructed irradiance value H^m), as shown in equation 2:

$$H_{Pi}[\%] = \frac{H_i}{H_i^m} \qquad (2)$$

This indicator has a major importance to quantify shading effect. "We found that orientation had very little effect. However, when surrounding obstacles were included, the energy consumption for each ilot increased since solar radiation falling on the facades was blocked and the resultant solar gains were reduced" (Crawford, 2002).

Other indicators point out the distribution of solar irradiation on roof, façade and ground. According to Okeil (2004) "solar energy falling on facades is the only part of solar energy that could be passively used without complicated mechanical equipment and expensive installations". In a more general manner, urban planning should tend to optimize solar radiation on roofs and facades in order to be able to use this renewal energy. Solar radiation distribution is expressed through equations 3-6:

Roof repartition: $H_r^d = \left(\sum_i^n H_{ri}\right) / \left(\sum_i^n H_i\right)$ (3)

Facade repartition: $H_f^d = \left(\sum_i^n H_{fi}\right) / \left(\sum_i^n H_i\right)$ (4)

Ground repartition: $H_g^d = \left(\sum_i^n H_{gi}\right) / \left(\sum_i^n H_i\right)$ (5)

And $H_r^d + H_f^d + H_g^d = 1$ (6)

Chatzidimitriou et al. (2004) also used these parameters, among others, to investigate design proposals for microclimatic modifications and potential improvements.

Iso-shadow

This indicator has been introduced by (Kristl et al. (2001). "Iso-shadows represent the ratio of incident solar radiation on a building or land to unobstructed solar radiation received at the same location during the chosen period of time, day or year, respectively". An example of iso-shadow is given Figure 3.

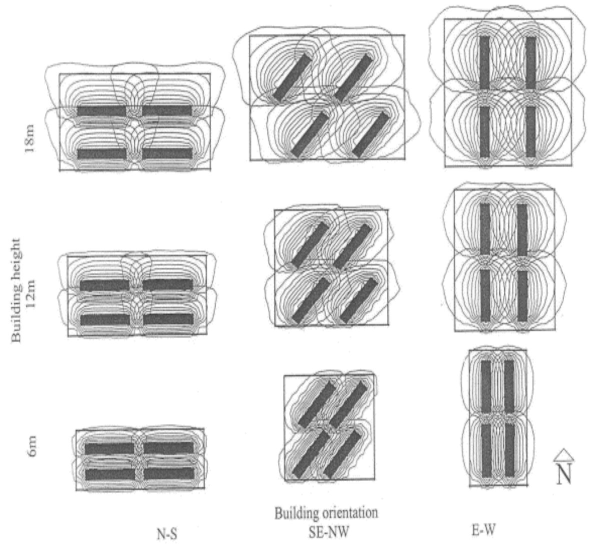

Figure 3: Yearly iso-shadows for 12 m wide buildings (Kristl et al., 2001)

This indicator is used to compare and characterize distances between buildings, their orientation, and the building geometry.

"Orientation rose"

Compagnon (2004) defined it as the facade surface area oriented towards each direction, weighted in function of sky view factors of each surface (see equation 7) and aggregated into several azimuth sectors s (typically 15° wide).

$$A_s\left(m^2\right)=\sum_i \frac{SVF_i}{0.5} A_i \qquad (7)$$

A_S is the total weighted facade area for the azimuth sector s and SVF_i represent the sky view factor of façade i. Coefficient of 0.5 is used because for an unobstructed vertical façade, SVF_i = 0,5 (i.e. the facade is exposed to half of the sky vault).

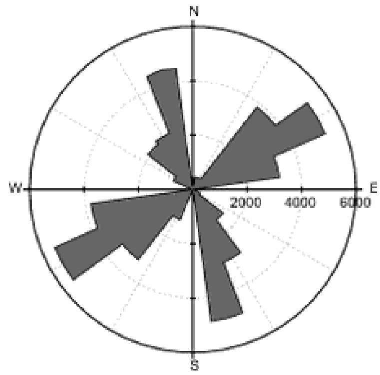

Figure 4 : Example of orientation rose (Compagnon, 2004)

"The sectors that contain the largest facade area indicate the main orientations affecting the solar and daylight access to the buildings. The purpose of an orientation rose is also to serve at the early stage of urban planning" (Compagnon, 2004).

Shadow density and daylight distribution

Ratti et al. (2003) used mean shadow density: "high values recorded in the streets are beneficial in hot-arid regions as they provide protection to pedestrians and to the horizontal street surface from solar radiation". They also used mean daylight distribution of all ground surfaces such as streets and courtyard floors to measure daylight benefits.

Shadow density Sh_d corresponds to the average number of hours of protection from direct irradiation from the sun (equation 8):

$$Sh_d = \frac{t_i^{sh}}{t_{daylight}} \qquad (8)$$

Daylight distribution Day_d is the average normalized direct daylight factor on a surface (equation 9):

$$Day_d = \sum_i^n \left(\frac{L_{gi}}{L_{gi}^m} \right) \qquad (9)$$

Values are normalized: 100% represents the illuminance that would fall on an unobstructed surface which sees the whole sky vault, 0% represents nil illuminance.

Sky view factor or sky opening

Ratti et al. (2003) introduced sky view factor as a "good measure of the openness of the urban texture to the sky, often associated, among other indicators, to the increase in temperature in the urban context compared with the surrounding rural context, referred to as the urban heat island phenomenon." Otherwise Teller et al. (2001) define sky opening as an indicator of "the perceptive confinement felt by an observer located in the open space". An example of sky view factor of a district is given Figure 5.

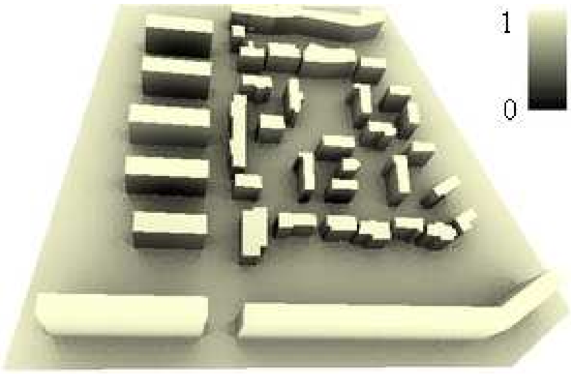

Figure 5: sky view factor of a district

Conclusion

At the scale of the district, solar indicators are diverse and usually need to be represented spatially. These indicators often demand exact values to be useful, and so simulation tools require reliable inputs such as climatic data, geometry or reflectance of surfaces. Apart from the orientation rose and the sky view factor, all the other indicators presented are 4D dependant indicators: they vary in time and in space. Urban planning through the utilization of this kind of indicator implies their accurate quantification. The user must define pertinent conditions such as duration of simulation or measurement, dimension of studied area, precision of simulation (e.g. meshing or time steps). In the next section, solar simulations have been run at the scale of the district with the SOLENE software.

SIMULATION

Aim of the simulation

The simulations done at the scale of the district are becoming primordial tools for urban planning. They are in our gasp thanks to the evolution in computer performance. However, this kind of simulation still remains a major time consuming step: a recurrent question concerns the optimization of the time span, the meshing and the necessary precision of surface reflectance. This choice is strongly depend on expectations, on studied indicators and on available data.

Yet, the influence of these parameters still remains hardly known at the scale of the district. Simulations have been run on a simplified case study in order to explore these issues.

Brief presentation of the case study

The case study is a part of a district located in North West of the city of La Rochelle (France). The major aspect is a rather high density of building. The geometry has been simplified in order to decrease calculation time as the shape of the buildings and their layouts are the geometrical key parameters for solar simulation. Height of buildings is between 23 and 28 meters.

Figure 6 introduces the denomination of the different buildings. Each building possess 5 faces which are named "_t", "_n", "_s", "_e" and "o" respectively for roof, face oriented to the north, the south, the east and the west.

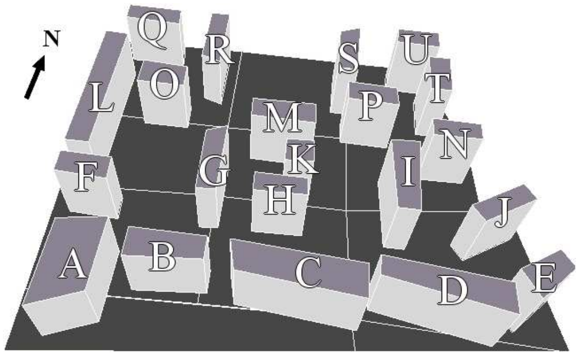

Figure 6: case study and names of building faces

Parameters

La Rochelle's latitude is 46°N and longitude is 1°W. Terrain is considered flat because of the very low difference of level of the entire area. One major parameter is the reflectance of each surface. Urban form has been divided into 3 kinds of surfaces: ground, building façade and building roof. In these studies, all the buildings are approximately of the same height. Therefore a variation of roof reflectance will not influence reflected irradiation receive by the district: roof reflectance is kept constant for all simulations.

All the facades of the buildings have the same reflectance and this value change from one simulation to another. The same treatment has been applied to the ground. Table 1 presents the variation of reflectance for the building facades and the ground.

Table 1: reflectance of the surfaces for each case

Case	1	2	3	4	5	6	7	8	9
facades	0.1	0.3	0.4	0.5	0.7	0.4	0.4	0.4	0.4
ground	0.1	0.1	0.1	0.1	0.1	0.3	0.5	0.7	0.9

According to measurements (Martin Centre for Architectural and Urban Studies, 1997), realistic reflectance values for facades are between 0.1 (dark brick façade) and 0.8 (white plaster façade) and for ground between 0.05 (dark asphalt) to 0.3 (clear concrete). Reflectance of the ground can be beyond 0.3 if all outdoor objects such as cars are considered. Roof reflectance has been set to 0.3, considering a white gravel roof.

A mesh (4824 mesh elements) was applied to the external envelope of the model and simulations have been run for a time span of one year. For each day of the year and for each surface, two variables are stored:

- the daily global solar radiation (direct + diffuse, before any reflection): $H^{inc}\_i(day)$
- the daily total solar radiation (direct + diffuse, after all reflections): $H\_i(day)$

Both variables are expressed in Wh/(m².day). The tool used, SOLENE, has been developed in the CERMA laboratory, Nantes (Miguet et al., 2002). This software simulates solar, luminous or thermal effects on outdoor conditions from a 3D model of the urban fabric. To run automated simulation over several months, a homemade C++ program has been developed to drive SOLENE.

RESULTS ANALYSIS

Basic case

Considering usual value for the reflectance of surface (0.3 for facades and 0.1 for the ground), the average global annual energy received for the area studied is 886 kWh/(m².year) without any reflection and 916 kWh/(m².year) after all reflections; that is to say a difference of 3.35 %.

Figure 7 show the proportion of reflected irradiation P^{Hrefl}_i received by each surface i of the district, calculated with equation 10 below.

$$P^{Hrefl}\_i(year) = \frac{H\_i(year) - H^{inc}\_i(year)}{H\_i(year)} \quad (10)$$

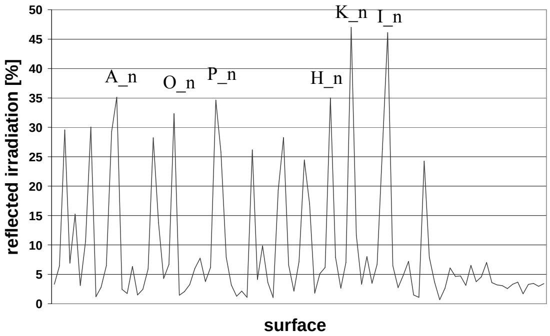

Figure 7: proportion P^{Erefl} for each surface

Very significant difference (at least 30%) is found for surfaces K_n, I_n, A_n, H_n, P_n and O_n. These surfaces are located in the core of the district therefore more irradiation is reflected to them. Maximum annual difference is obtained for surface K_n (building K, face oriented to north).

Figure 8 shows the daily evolution of (H_i/H^{inc}_i) ratio for each surface.

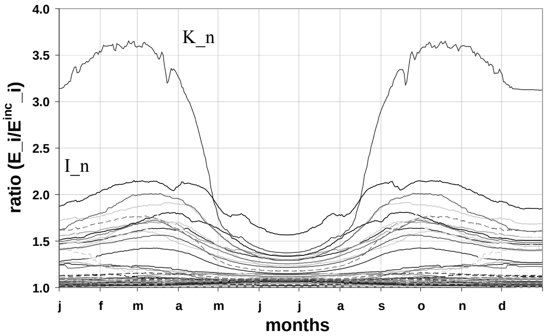

Figure 8: annual variation of (H_i/H^{inc}_i) ratio: each curve represents a surface

Ratios vary in time: low values correspond to the months of May, June and July; i.e. when the sun is high in the sky. During this season, direct irradiation beams are the most vertical and so reflected irradiation is directed to the sky and lost. Ratios close to 1 (nil reflectance) correspond to roofs surfaces, to the surfaces facing the outside of the studied area (very low view factor) and to the surfaces which have no building directly opposite.

Figure 9 presents the typical annual variation of global irradiation (incident + reflected) for each façade of building; the behavior of building I is representative of the majority of the others buildings.

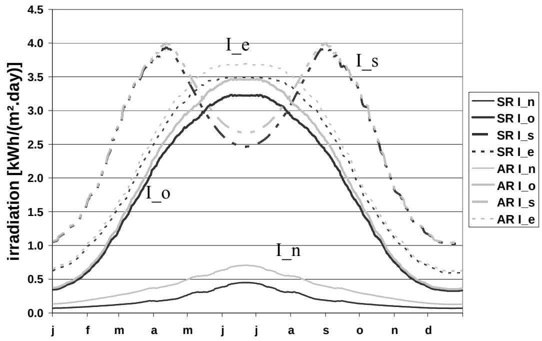

Figure 9: annual variation of irradiation without (SR) and with (AR) reflections for each facade of building I

Considering daily irradiation, reflected proportion has a low influence. However, as shown in Figure 7, integrated annually this difference becomes enough significant to be considered. Figure 9 also shows that south-facing façade has a different behavior than other facades. Furthermore, simulations have permit to compare daily irradiance of all the different facades with same orientation. All ground surfaces have the same trend during the year; it is also the case for surfaces facing south and north. Whereas east and west oriented facades have different behavior, as shown in Figure 10 for east-facing facades.

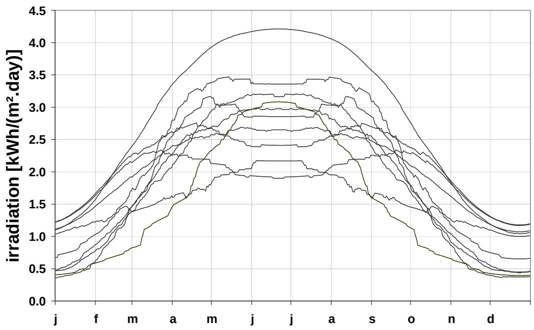

Figure 10: annual variation of irradiation with reflections for different east-facing facades

Figure 9 and 10 show that in the case of significant density district, results for a unique day cannot be generalized to longest periods such as the month or the season. This discrepancy is due to shading effect and the reflectance of surface increases this phenomenon. In the following, reflectance of surface is further investigated.

Variation of the reflectance of facades

The simulations conducted in this section correspond to case 1 to 5 (Table 1) and concern the buildings located in the core of the studied area (i.e. G, H, I, K, M, O and P). For each orientation of surface, the daily proportion of irradiation reflected received P^{Hrefl}_core has been investigated. Figure 11 presents the results corresponding to south-facing facades.

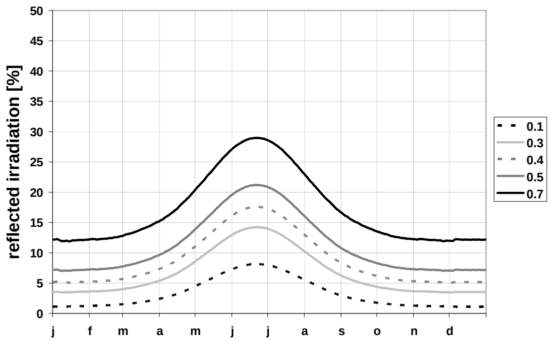

Figure 11: proportion P^{Hrefl}_core of south oriented facades for different façade reflectance

Discrepancy between each surface orientation is observed. Results also show low variation for south and east orientated facades: the direct irradiation is predominant in these cases. Irradiation of façades facing north and west are lowest for high position of sun because the vertical position of the sun limits the reflection. North orientation is the orientation where the maximum reflected irradiation is obtained due to the absence of direct irradiation.

Figure 12 shows the results of the daily proportion of irradiation reflected received by ground.

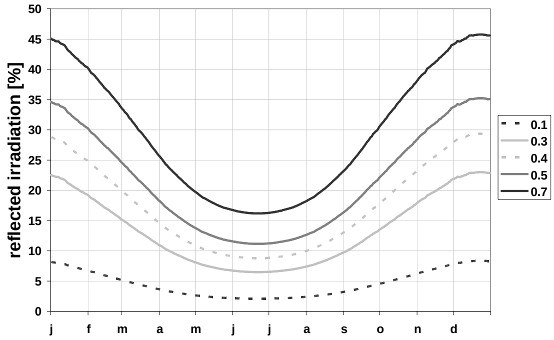

Figure 12: proportion P^{Hrefl}_core of the ground during the year, for different façade's reflectance

Variation of the proportion of reflected irradiation received by the ground is of the opposite of sun's azimuth: due to the mask effect from buildings, low direct irradiance and high reflected irradiation is found when the solar height is low.

Variation of the reflectance of ground

The same study as previously is conducted, but reflectance of facades is kept to 0.4 and reflectance of ground varies (case 3 and 6 to 9, Table 1).

Figure 13 presents the results corresponding to south-facing facades. Significant values are observed during the summer season.

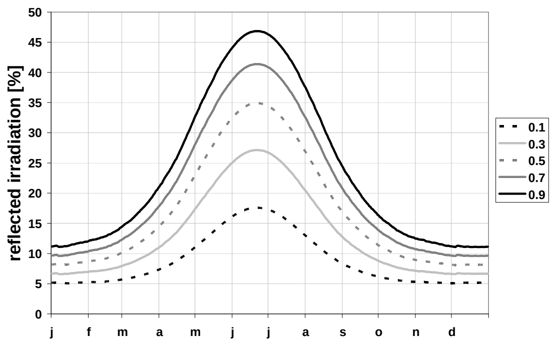

Figure 13: proportion P^{Hrefl}_core of south oriented facades for different ground reflectance

Compared to Figure 11, Figure 13 has more significant summer values for the same winter values. The same phenomenon is found for all other orientations of façade, but it has less importance for north and west oriented facades. Consequently, the major part of reflected irradiation received during summer season is coming from the ground.

As expected, reflectance of the ground has no influence on reflected irradiation received by the ground because view factor between ground surfaces is null.

DISCUSSION AND CONCLUSIONS

Basic case analysis

Case 2 (Figure 7) has shown the importance of reflected irradiation: it can represent more than 30 % of the irradiation received by a surface. Obviously, the proportion of irradiation reflected increase with the density of buildings around the simulated surface: to maximize the reflection proportion, surface must be close to another building (to increase the view factor). High density districts save thus statistically more reflected irradiation than low density ones. It should be noted that increasing the density of a district will also conduct to the decrease of incident irradiation on surface; as the number of masks is increasing too. The solution which consists to increase density of building is thus advisable when the aim is to increase reflected irradiation and decrease incident radiation.

Figure 8 points out that importance of reflected irradiation varies during the year. And low value corresponds to high solar height, when direct irradiation is vertical. However it remains significant all the year for most surfaces. Moreover, north oriented surface have the most significant proportion of reflection irradiation because they are not exposed to direct solar irradiation.

Concerning time span, in the case of significant density districts, results for a unique day cannot be generalized to longest periods such as the month or the season. This discrepancy is due to shading effect; and the reflectance of surface increases this phenomenon. Further investigations are needed to quantify the error involved by this simplification.

Reflectance variation analysis

Trends are different for each façade orientation, depending mostly of direct irradiance received. High reflectance for façade increases reflected irradiance during all the year except in summer season and permit to use wisely solar energy. Concerning east and south oriented facades, reflected irradiance has less importance. And a higher value for ground irradiance increases reflected irradiance during summer season.

Discussion upon indicators

The indicators presented in this paper concerns mostly energy aspects and further investigation are needed to widen range to aspects such as outdoor comfort and visual impact. This consideration is a part of the global study on how to use solar indicators at the scale of the district in order to assess a project of district.

Simulations clearly demonstrate that reflection must be taken into account for the accurate quantification of indicators such as solar irradiation, spatial distribution of irradiation and potential irradiation. Reflected irradiation indeed varies from one orientation of façade to another. Consequently, solar simulation should include reflectance of surfaces, even at early stage of design if it is possible.

Daylight distribution is depending on reflected illuminance, unlike shadow density. Consequently, in hot and arid climate, a theoretical way to increase shadow density while increasing daylight distribution may be to increase density of buildings and reflectance of façade.

SCOPE

This paper has shown the importance of shading effect and inter-reflection between buildings of a district. Both have to be taken into account during solar simulation and use wisely at the planning stage. To draw more general conclusion on the time span of simulation and its consequences, more simulations are required. The scope of these simulations will be enlarged to various kind of density and to different meshing characteristics of the model. The next step concerns variation of reflectance in a district where roofs have significant difference of height.

Concerning solar indicators, spatial indicators are being investigated. The assessment of a district requires that spatial representation is simplified into one or several variables such as average value, maximum or minimum value… These investigations are of major importance for the global assessment of district projects. Others investigations concerning the set of solar indicators defined are also expected: weight of each indicator, aggregation method…

Solar aspect is a step toward the global assessment, involving all aspects allowing being as exhaustive as possible. Next step will concern acoustic aspects and energy aspects.

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NOMENCLATURE

A_i	area of façade i [m²]
A_S	total weighted facade area for the azimuth sector s [m²]
Day_d	daylight distribution [%]
H_i	irradiation of a surface i [Wh/m²]
H_{fi}	irradiation of facade i [Wh/m²]
H_{ri}	irradiation of roof i [Wh/m²]
H_{gi}	irradiation of ground i [Wh/m²]
H_r^d, H_f^d, H_g^d	respectively proportion of irradiation on roofs, facades and ground [%]
$H^{inc}\_i(t_s)$	global irradiation of surface i, without any reflection for a time step t_s [Wh/m²]
$H\_i(t_s)$	global irradiation of surface i after all reflections for a time step t_s [Wh/m²]
H_i^m	maximum irradiation of a surface i, considering no shading effect [Wh/m²]
H_{Li}	spatial irradiation level of a surface i [%]
H_{Pi}	potential irradiation of a surface i [%]
L_{gi}	global illuminance of surface i [lux]
L_i^m	maximum global illuminance of surface i, considering no shading effect [lux]
n	number of surfaces of the studied area
s	azimuth sector [°]
Sh_d	shadow density [%]
SVF_i	sky view factor of façade i [-]
$t_{daylight}$	duration of daylight at a specific location
t_i^{sh}	duration of shadow on a surface [hours]
t_s	time step (e.g. day, month, year…)