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DOMUS METHOD FOR PREDICTING SUNLIT AREAS ON INTERIOR SURFACES

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ABSTRACT

Solar direct gain is responsible for a substantial impact on the thermal and energy behavior in buildings. Most existing building energy simulation tools neglect the effect of the evolution of the sun patch position on the internal surfaces, which can have a great influence on the prediction of the indoor thermal comfort. In the current software, the direct solar radiation that enters through the windows is totally projected on the room floor or a distribution coefficient for internal surfaces is applied. However, techniques such as the ones based on pixel counting, implemented for the calculation of the direct solar distribution within buildings in the Domus program, have improved the accuracy and speed of calculations of incident solar radiation, especially for buildings with complex geometries. In this context, this paper presents an application and a comparative validation of the pixel counting technique implemented in Domus software for calculating the distribution of sun patch on building interior surfaces. Two case studies are simulated and the sunlit fraction and position results of the sun patch from Domus are compared with the ones produced by Shading SketchUp plug-in, which also uses pixel counting for calculating the internal solar distribution. The results indicate the important benefit of pixel counting: a fast technique that has no limitations regarding building geometry. Indeed, it can handle hollowed and non-planar polygons and curved geometries without a significant increase in the computational time or loss of numerical accuracy.

Keywords: building energy simulation, sun patch, pixel counting technique.

RESUMO

O ganho solar direto é responsável por um impacto substancial no comportamento térmico e energético em edifícios. A maioria das ferramentas atuais de simulação energética de edifícios negligencia o efeito da evolução da mancha solar nas superfícies internas, o que pode ter uma grande influência sobre a avaliação do conforto térmico da edificação. De modo geral, a radiação solar direta que entra pelas janelas é projetada totalmente no piso do ambiente ou um coeficiente de distribuição para superfícies internas é aplicado. No entanto, técnicas como as baseadas na contagem de pixels podem melhorar a precisão e a velocidade dos cálculos da radiação solar incidente, especialmente para edifícios com geometrias complexas. Neste contexto, este trabalho apresenta uma aplicação e uma validação comparativa da técnica de contagem de pixels implementada no software Domus para o cálculo da distribuição da mancha solar nas superfícies internas do edifício. Dois estudos de caso são simulados e os resultados de área e posição da mancha solar do programa Domus são comparados com os produzidos pelo plug-in Shading SketchUp, que também usa contagem de pixels para calcular a distribuição solar interna. Os resultados indicam as principais vantagens da contagem de pixels: uma técnica rápida que não tem limitações quanto à geometria do edifício. De fato, ela pode lidar com polígonos vazados e não-planares bem como geometrias curvas sem um aumento significativo no tempo computacional ou diminuição da precisão numérica.

Palavras-chave: simulação energética de edifícios, mancha solar, técnica da contagem de pixels.

1. INTRODUCTION

Building design is currently going through a period of considerable changes. With the growing concern over climate changes, the depletion of fossil fuel stocks, and the increasing attention of the relationship between the indoor environment and the health of the occupants, the techniques of building design and construction seek to ensure the reduction of energy consumption and the supply of comfortable indoor environments for occupants. In order to support design decisions for energy efficient buildings, computer simulations have been substantially used.

Building energy models have been employed since late 60s, being primarily used for sizing heating, ventilating and air conditioning equipment. After the oil crisis in the 70s, greater attention has been devoted to passive and innovative design strategies, which required the development of a new generation of building energy simulation (BES) tools (JUDKOFF, 1988). In addition, the application of these tools is being currently promoted around the world by green building certifications, such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method), because the verification of the minimum levels of thermal comfort, daylight and energy performance of buildings can be performed efficiently through computer simulation. Thus, the success of energy-efficient design, labeling, rating and retrofit efforts depends largely on the accuracy of the analysis performed for each task (POLLY et al., 2011). As a result, the development, evaluation and standardization of models and programs must be continually reviewed and improved to model more complex and detailed systems.

The direct solar radiation that falls on the internal surfaces is one of the factors responsible for the thermal gain in a building. As consequence, a precise simulation of the conditions of direct solar incidence is essential for a good prediction of whole-building energy and thermal performance. Technically speaking the evaluation of the direct solar radiation, its evaluation requires the calculation of the sunlit area (A_{sun}) that depends on the Sun position and obstruction surface geometry (ENERGYPLUS, 2016).

Concerning the distribution of direct solar radiation transmitted through windows, a simpler model is used in most BES tools, assuming that all beam solar strikes on the floor homogeneously (HENSEN; LAMBERTS, 2011). Although an uniform distribution of the solar heat flux on the surfaces may be enough to one dimensional calculation models (commonly used in most BES tools), some researches have shown that the simplification or negligence of the sun patch distribution yields a large difference on the simulation results, especially for heating requirements of glazed rooms (WALL, 1997; TITTELEIN, 2008). A precise sun patch location can refine the calculation of superficial and air temperatures as well as mapping the mean radiant temperatures for the predictions of comfort index (RODLER, 2014). Moreover, the improvement of sunlit pattern calculation as a boundary condition is fundamental for the three-dimensional (3D) heat transfer models (RODLER et al., 2013; RODLER et al., 2013; MENDES et al. 2016). Rodler *et al.* (2016) have highlighted the contribution of a 3D thermal model with the sun patch location to evaluate highly insulated and low energy consumption buildings, which are highly sensitive to internal gains.

Taking into account the aforementioned facts, and also because the computational resources have been significantly increased in the last decades, it is time to improve the calculation of the shadowing and insolation distribution on building surfaces. The most common strategy for calculating sunlit area is the polygon clipping (PgC) which uses projection and successive clipping of polygons. Although the PgC based methods are used by many simulation programs - such as ESP-r, BLAST, DOE-2, TRNSYS and EnergyPlus - they have some limitations regarding the type and number of polygons. Additionally, the computational time is strongly dependent on the desired accuracy. For improving this task, the pixel counting technique represents a powerful method and has been implemented in Domus[1], which is an user-friendly software for whole-building hygrothermal and energy simulation, developed by the Thermal Systems Laboratory at Pontifical Catholic University of Parana - PUCPR (MENDES et al., 2003)

Introduced by Yezioro and Shaviv (1994), the pixel counting technique (PxC) can calculate, for each time step of simulation, the sunlit area on the building envelope. Basically the technique relies on rendering the geometry of the building using an orthogonal projection from the vantage point of the Sun and the sunlit fraction associated to each surface is determined by means of a pixel counting scheme. The authors implemented the technique and made it available in plugin Shading for SketchUp[2].

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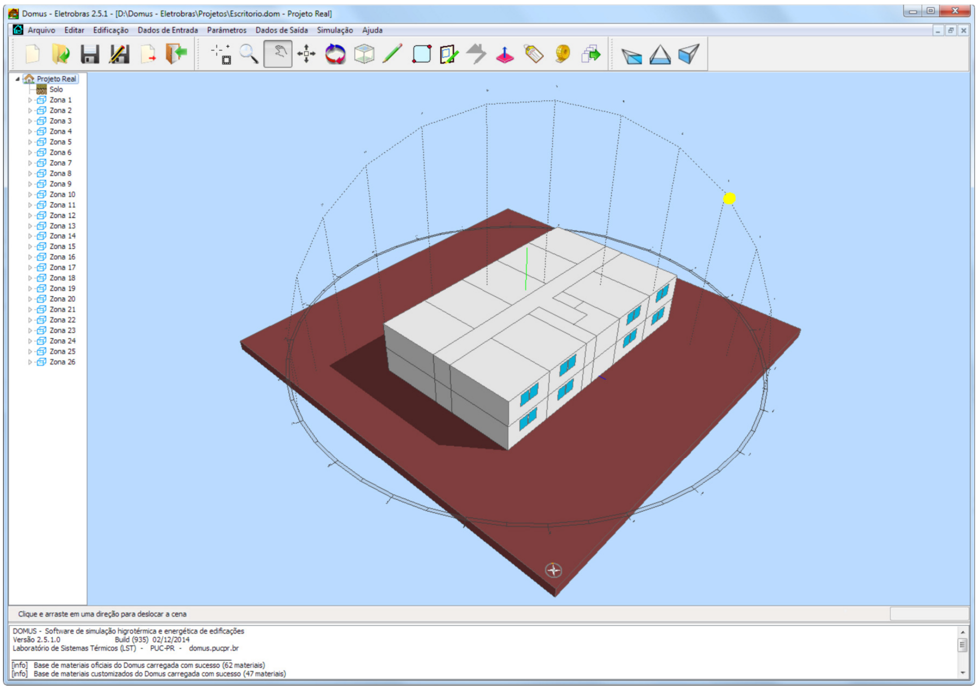
[1] https://domus.pucpr.br/

[2] https://www.sketchup.com/pt-BR

Jones *et al.* (2012) explored some occlusion techniques available in OpenGL for the improvement of the pixel counting approach of Yezioro and Shaviv (1994). OpenGL is a hardware accelerated graphic library largely employed to produce interactive 3D computer graphics applications (SHREINER et al., 2013). Particularly in the context of pixel counting, the cross-platform is used to render the scene and query the number of updated pixels belonging to the surface. According to Jones *et al.* (2012), OpenGL requires very little computational time to render large scenes, improving the computational efficiency of the technique, especially when applied to complex geometries.

Although the technique is not exact due to the effect of pixellation, Jones *et al.* (2012) have already shown that the technique can be effective to calculate the sunlit fraction on the facade of a building. They have compared results of projected sunlit surface fraction (PSSF) obtained by PxC with analytical solutions and the results showed that the incident beam radiation calculated using PxC was within 1% of the analytical value. Besides, the technique had no difficulty to deal with concave or rounded surfaces, being also capable to deal with complex double curvature or hollowed surfaces. Despite all those advantages, the PxC has not yet been evaluated on a BES software.

Pixel counting technique has been recently implemented in Domus software (Figure 1) using OpenGL and following the approach proposed by Jones *et al.* (2012). Currently, the pixel counting is used to calculate the sunlit fraction and direct solar energy on exterior and interior surfaces that affect the whole-building energy and thermal performance. Indeed, the results of sunlit area are used to predict different parameters, such as the direct radiation on surfaces and solar heat gain within building's room. Additionally, the results of direct solar energy can be coupled to the prediction of photovoltaic and solar collector systems performance.



Clique e arraste em uma direção para deslocar a cena

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DOMUS - Software de simulação higrotérmica e energética de edificações
Versão 2.5.1.0                Build (935)  02/12/2014
Laboratório de Sistemas Térmicos (LST) -  PUC-PR -  domus.pucpr.br

[info]  Base de materiais oficiais do Domus carregada com sucesso (62 materiais)
[info]  Base de materiais customizados do Domus carregada com sucesso (47 materiais)
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Figure 1 – Graphical interface of Domus software

2. OBJECTIVE

The objective of this paper is to present an application and a comparative validation of a pixel counting technique implemented in Domus software for calculating the distribution of sun patch on building interior surfaces.

3. METHOD

Two case studies were investigated in order to explore the capabilities of the pixel counting technique implemented in Domus software in calculating sun patch distribution on interior surfaces. The first case is a single zone, with interior dimensions of 3.00 x 2.90 x 2.80 m, and a window with clear glass of 1.40 x 1.40 m located on the western facade (Figure2a). The second case is also a single zone, with interior dimensions of 3.00 x 2.90 x 2.80 m, but the window has dimensions of 2.70 x 1.40m with a hollowed shading elements called cobogó. Those elements - inspired by moucharaby, traditional feature from Arabic architecture - were created in 1929 by three people who worked in the building construction sector. They consist of wood grills or lattices installed on the building balconies and windows. The Cobogó name derives from the three creators' surnames: Amadeu Oliveira COimbra, Ernest August BOeckmann and Antonio de GÓis. Besides the aesthetic function, its use may provide different sustainable architecture strategies, such as solar radiation control, daylight, natural ventilation and exterior views.

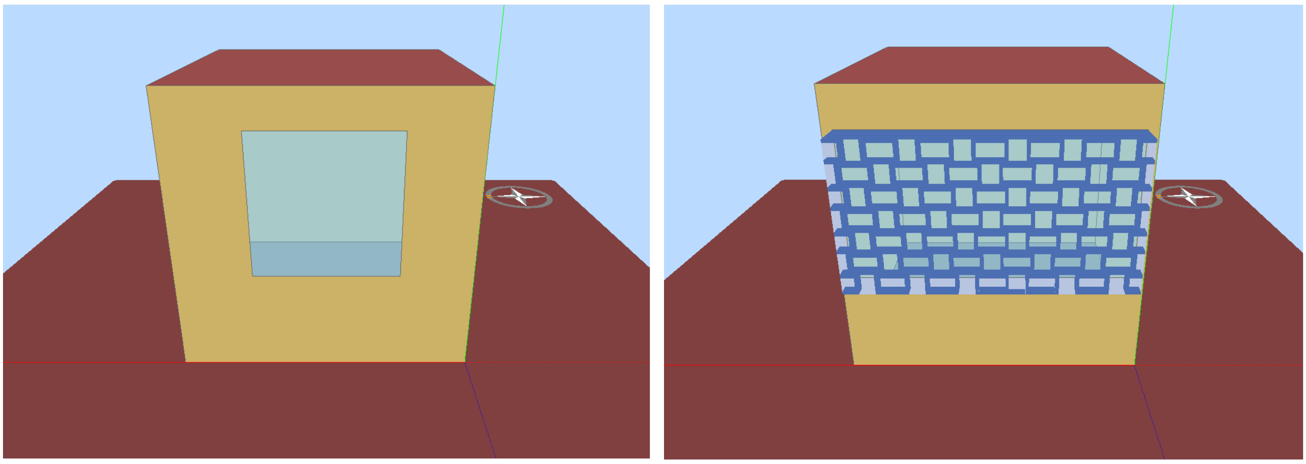
(a) (b)

Figure 2 - Case studies: (a) simple case; (b) complex case.

As the calculation of the sun patch depends exclusively on geometric information, such as building geometry and orientation and Sun position, the materials of the walls, floor and roof do not change the results of the area and position of sun patch on the interior surfaces.

The simulations were performed for the city of Curitiba (25.52S latitude and 49.17W longitude) and the sunlit area was calculated on the interior surfaces (floor, South-oriented, North-oriented and Est-oriented surfaces) for two specific days in order to have a representative study in the whole year: June 21st and December 21st. Table 1 summarizes the set of simulations performed for both cases.

Table 1 – Summary of case study simulations

Case study	Two: Simple and complex models
Simulated Surfaces	Floor, South-oriented, North-oriented and East-oriented surfaces
Location	Curitiba, Brazil (25.52S latitude and 49.17W longitude)
Run Period	June 21st and December 21st

The simulations were also performed by using Shading II SketchUp plug-in to validate the sunlit area results from Domus. Although Shading II SketchUp plug-in calculates the sunlit area on surfaces by using pixel counting technique, their results are not integrated to a building energy simulation tool. Thus, two results were required of the simulations using Domus and Shading II SketchUp plug-in: (1) sunlit fraction and (2) sun patch position on the interior surfaces. The sunlit fraction was simulated for each 15-minute interval of the afternoon period (since the window is western-oriented) of the days June 21st and December 21st on the floor, South-oriented, North-oriented and Est-oriented surfaces. The sun patch position provided by Domus were compared with images produced by using shadow functionalities of SketchUp. Both images from Domus and SketchUp were overlapped using an image processing software, called Adobe Photoshop CS3. This comparison was performed for the following surfaces and instants:

Table 2 – Summary of images used for comparison of sun patch position

Case	Surfaces	Instants
Simple case	South-oriented	June 21st – 15h00
	Floor	June 21st – 15h00 December 21st – 15h00
Complex case	South-oriented	June 21st – 15h00
	North-oriented	December 21st – 15h00
	Floor	June 21st – 15h00 December 21st – 15h00

4. RESULTS

In this section, sunlit fraction results from Domus and Shading II SketchUp plug-in simulations are compared for two case studies - simple and complex cases, and presented, respectively, in Figures 3 and 4.

In general, for the case 1 - simple, the results from Domus and Shading, in Figure 3, are similar. The highest difference of the results occurs in the South-oriented surface at 16h15 on June 21st. The sunlit fraction from Domus is 33.3% and, from Shading, is 39.3%. In fact, it is observed a certain inconstancy of the results from Shading, in particular, at the moment when there is a peak of solar incidence on the surface, such as at 16h15 on June 21st, the moment with the highest difference between Domus and Shading results. On the other hand, Domus predicts continuous evolution of the sunlit calculated area, without abrupt variations that reveals a more physically consistent algorithm.

For the case 2 – complex case, the highest difference of the results occursat the floor surface at 15h30 on June 21st. The sunlit fraction from Domus is 8.4% and, from Shading, is 17.1%. Despite this difference, the sunlit fraction results present a coherence between them, however, it is still noticed that the results from Shading maintain a certain inconstancy, with regions of abrupt elevations and depressions. Although Shading and Domus use the same technique to calculate the sunlit surface area, other factors may lead to this difference between the programs, such as the calculation of the Sun position (azimuth and altitude angles) or the way the pixel counting technique was implemented.

It is important mentioning that the Case *b* demonstrates the capability of pixel counting technique for simulating complex geometries, such as hollowed elements. Most of solar shading calculation algorithms implemented in building energy simulation tools are limited to a few simple shading devices. In fact, they are not able to deal with polygon with holes or curved geometries. On the other hand, the simulation tests indicate the opportunity to simulate complex architectural models as the most important advantage of pixel counting technique, which is free of geometrical limitations.

Relating the sun patch position, Figures 5 and 6 show that the results from Domus and shadow functionalities of SketchUp have a good agreement. The white region represents the sun patch provided by SketchUp and, the orange outline is from Domus. For both cases, the results of sun patches are almost totally overlapping, which indicates the coherence of the results from pixel counting technique implemented in Domus.

It is worth noting that the sun patch on surfaces varies widely throughout the year, which is represented in this paper by two days with extreme values of direct solar incidences. This demonstrates that a simplified model for the direct solar radiation in building enclosures - mainly when it is assumed that the solar beam homogeneously strikes the floor area - may neglect important variations of solar gains.

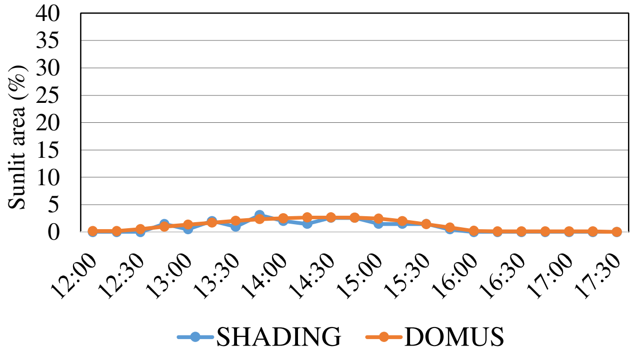

Figure 3a - Floor – June 21st

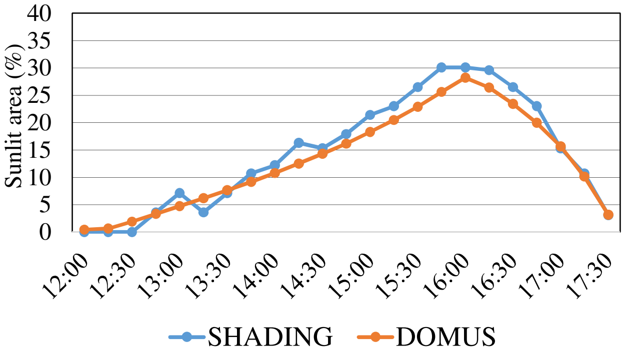

Figure 3b - Floor – December 21st

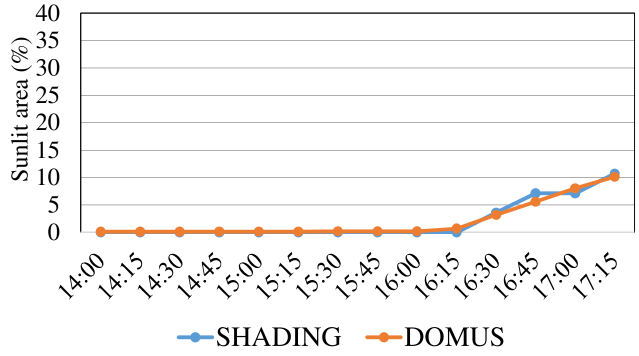

Figure 3c - Est-oriented – June 21st

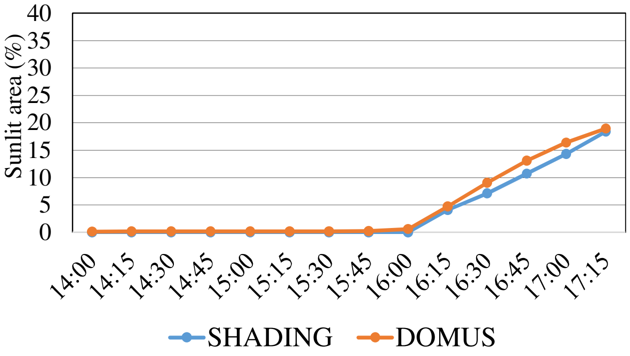

Figure 3d - Est-oriented – December 21st

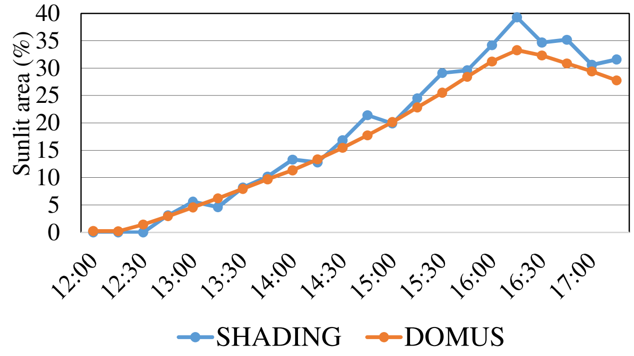

Figure 3e - South-oriented – June 21st

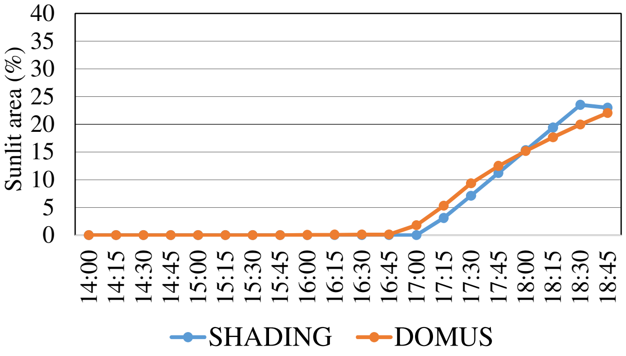

Figure 3f - North-oriented – December 21st

Figure 3 - Sunlit fraction results from Domus and Shading II SketchUp plug-in for the simple case study

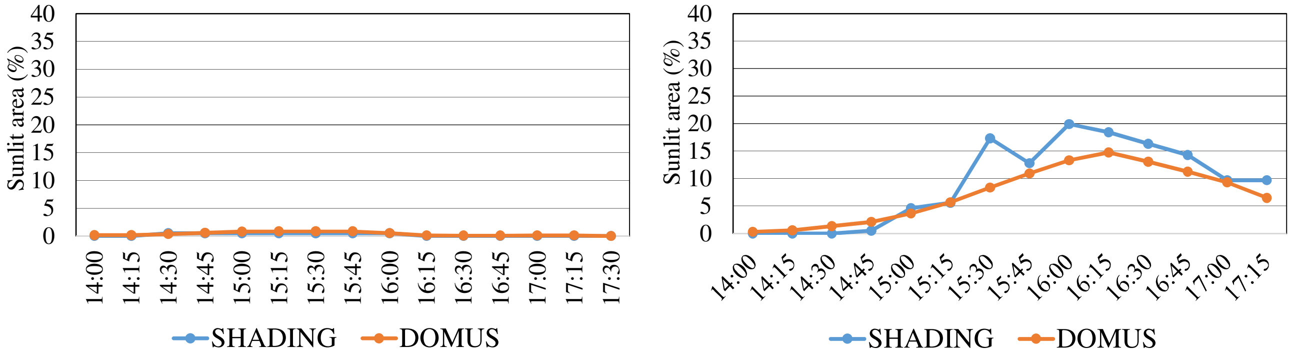

Figure 4a - Floor – June 21st

Figure 4b - Floor – June 21st

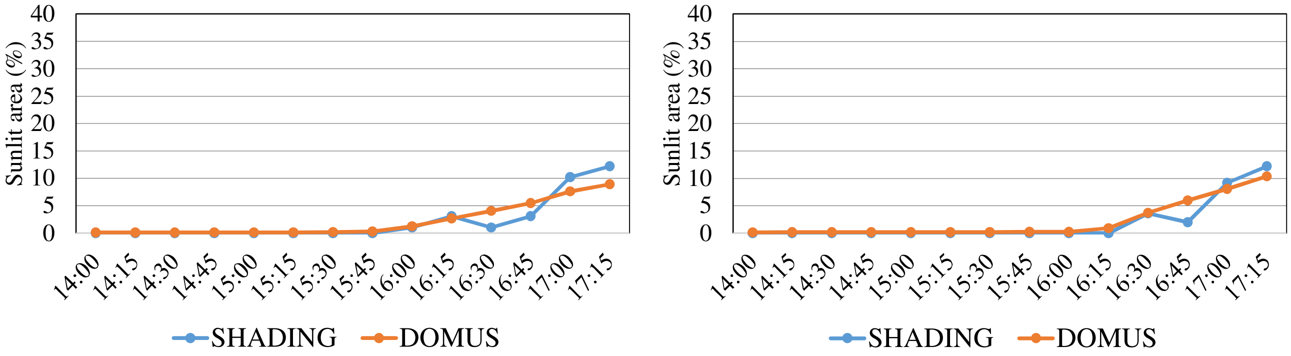

Figure 4c - Est-oriented – June 21st

Figure 4d - Est-oriented – June 21st

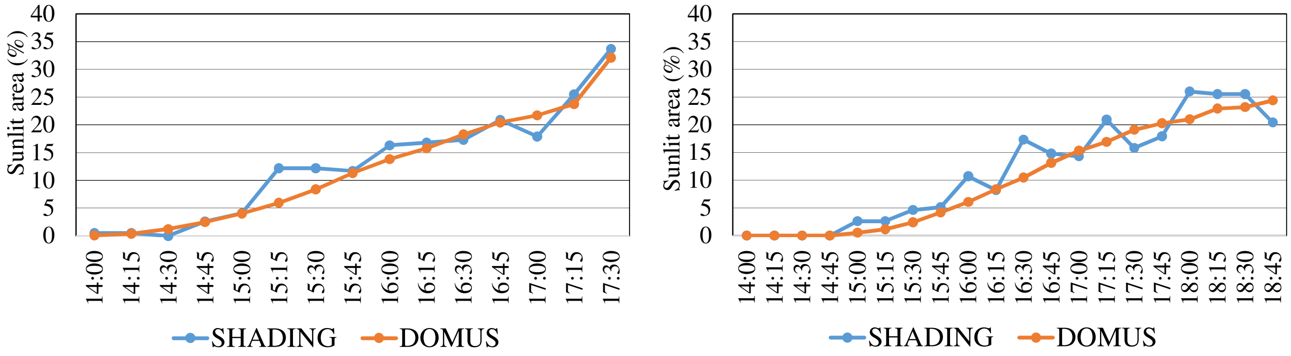

Figure 4e - South-oriented – June 21st

Figure 4f - North-oriented – December 21st

Figure 4 - Sunlit fraction results from Domus and Shading II SketchUp plug-in for the complex case study

Figure 5a - South-oriented– June 21st – 15h00 Figure 5b - Floor – June 21st – 15h00 Figure 5c - Floor – December 21st – 15h00

Figure 5 – Sun patch positions from Domus and Shading II SketchUp plug-in for the simple case study

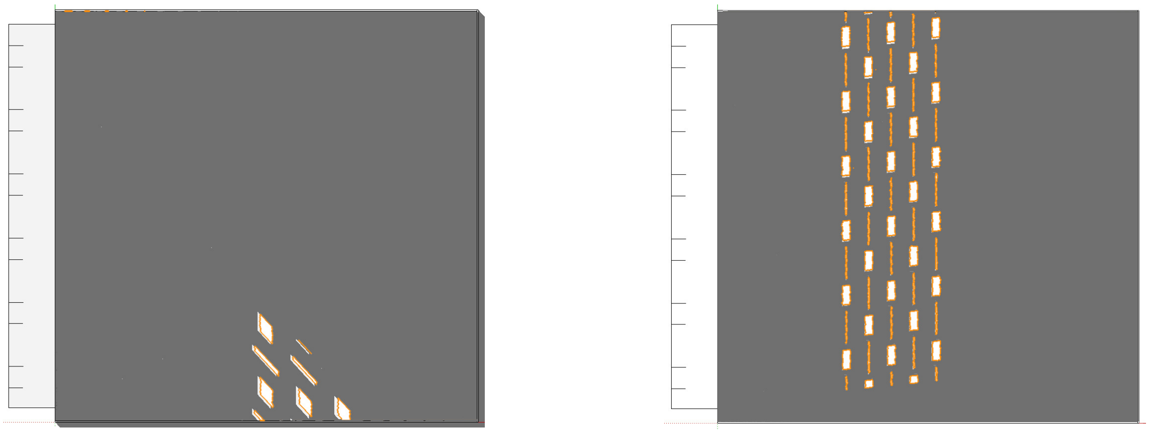

Figure 6a - Floor – June 21st – 15h00 Figure 6b - Floor – December 21st – 15h00

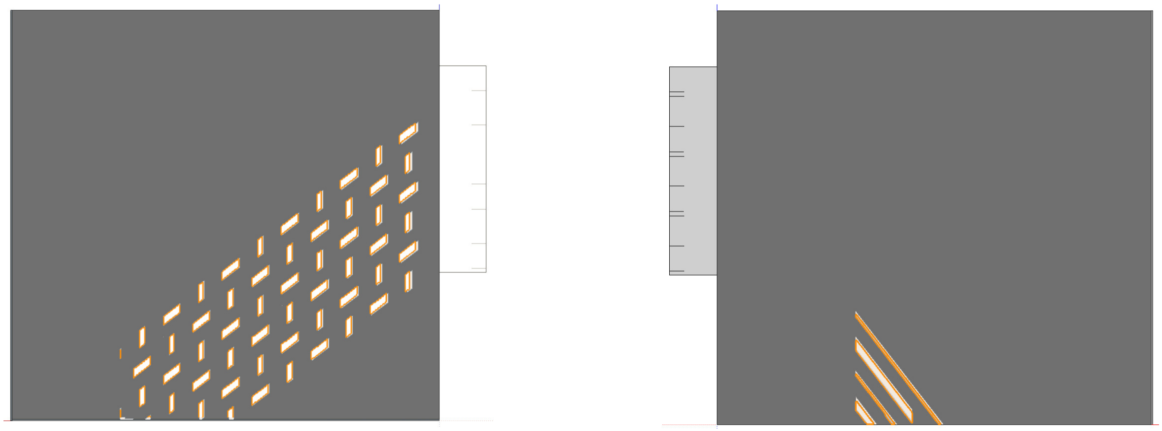

Figure 6c - South-oriented – June 21st – 15h00 Figure 6d - North-oriented – December 21st – 15h00

Figure 6 – Sun patch positions from Domus and Shading II SketchUp plug-in for the complex case study

5. CONCLUSION

The direct solar radiation that falls on the internal surfaces is one of the factors responsible for the thermal gain in a building. A precise simulation of the conditions of direct solar incidence in terms of area and the geometric position is essential for the determination of the boundary conditions for three-dimensional thermal simulations. Generally, in the current BES software, the direct solar radiation that hits the windows is totally projected on the room floor or a distribution coefficient for internal surfaces is applied. However, techniques based on image processing, such as pixel counting, implemented for the calculation of the direct solar distribution within buildings in the Domus software, have improved the accuracy and speed of calculations of incident solar radiation, especially for buildings with complex geometries. In this context, this paper presented an application and a comparative validation of a pixel counting technique implemented Domus software for calculating the distribution of sun patch on building interior surfaces. For that, two case studies were investigated and the sunlit fraction and position results of the sun patch from Domus were compared with ones from Shading SketchUp plug-in, which also uses the pixel counting technique for calculating the internal solar distribution.

The software comparative work has shown that, for both case studies, Domus and Shading SketchUp plug-in present similar values of sunlit fraction, although the results from Shading SketchUp plug-in were relatively unstable. Regarding the sun patch location, the results are almost totally overlapping, which indicates the coherence of the results from pixel counting technique implemented in Domus. It is worth mentioning that the second model has a complex shading element on the facade - cobogó. In general, the algorithms based on geometric analysis (shadow projections), such as polygon clipping, cannot handle hollowed polygons and curved geometries. Thus, that case study indicates the possibility to simulate complex architectural models as the most important advantage of pixel counting technique, which has no geometrical limitations. Indeed, it can handle hollowed and non-planar polygons and curved geometries without a significant increase in processing time.

Although Shading SketchUp plug-in uses pixel counting technique, their results are not integrated to a building energy simulation software. Thus, Domus is the first simulation tool that has adopted the pixel counting technique to calculate the sunlit external and internal areas. Besides not having limitations regarding building geometry, the pixel counting technique has an advantage with respect to computational cost. In general, it requires a lower run time when compared with algorithms based on shadow projections. The only limitation is the requirement of a hardware accelerated graphic card, that cannot be considered as a drawback since they are popular nowadays in personal computers.

Finally, we can also mention that pixel counting enables more accurate prediction of energy consumption and thermal comfort, besides the capability to be precisely integrated to 3-D CFD tools. As prospect for future work, research will be conducted to an experimental validation and inter-software comparison for common cases in the literature, such as Bestest.

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