'15 PLEA
Architecture in (R)Evolution
Bologna, 9-11 September

A DESIGN TOOL TO OPTIMIZE SOLAR GAINS AND ENERGY USE IN NEIGHBOURHOODS

Damien Trigaux	KU Leuven, Department of Architecture	damien.trigaux@asro.kuleuven.be
Bernard Oosterbosch	KU Leuven, Department of Architecture	bernard.oosterbosch@gmail.com
Karen Allacker	KU Leuven, Department of Architecture	karen.allacker@asro.kuleuven.be
Frank De Troyer	KU Leuven, Department of Architecture	frank.detroyer@asro.kuleuven.be

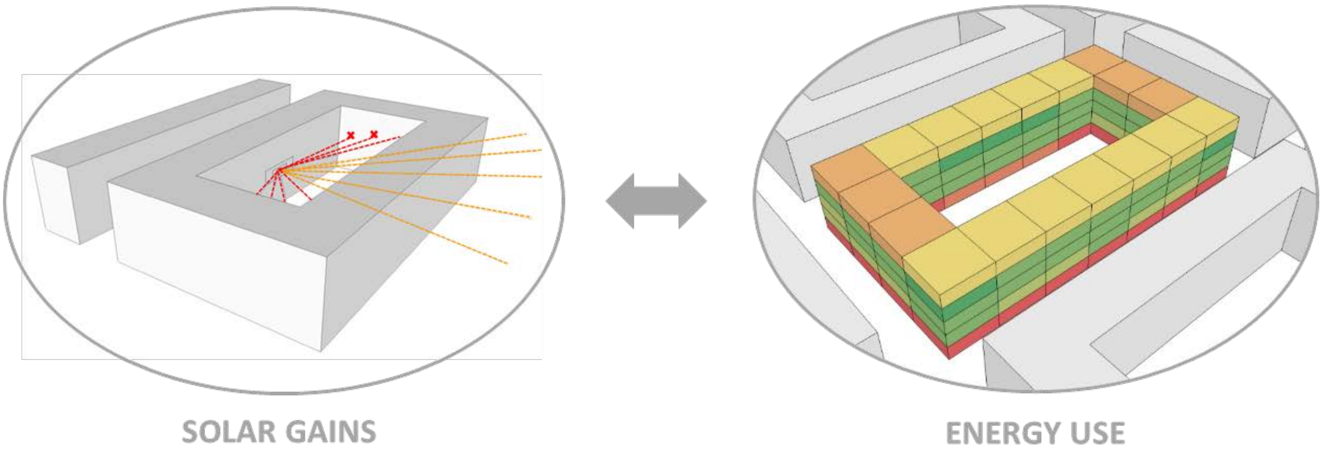


Fig 1: Design tool for the optimisation of solar gains and energy use in neighbourhoods

WHICH ARE YOUR ARCHITECTURAL (R)SOLUTIONS TO THE SOCIAL, ENVIRONMENTAL AND ECONOMIC CHALLENGES OF TODAY?

Research summary

In cold and moderate climates, the optimisation of solar gains is an important issue to answer the challenge of reducing energy expenditures in buildings. During the master planning of neighbourhoods, design decisions related to the urban layout and geometry can affect the availability of solar radiation considerably. However the impact of those decisions on the heating energy consumption is often neglected because of the lack of appropriate energy simulation tools.

This paper proposes a simple design tool to optimise solar gains and energy use during the master planning phase of neighbourhoods. Using a plugin, implemented in the 3D modelling software SketchUp, detailed information on solar obstructions is extracted from a 3D neighbourhood model. This information can be visualised on sun-path diagrams and linked to a simplified calculation method to assess the neighbourhood energy consumption. Simulations of an urban building block with the developed design tool show a good level of correspondence with results based on more advanced calculations with EnergyPlus.

Keywords: 3D environment, solar obstructions, sun-path diagrams, solar gains, energy use.

1. Introduction

In the context of passive and low energy architecture, the optimisation of solar gains is an important issue to decrease the heating energy consumption in buildings in cold and moderate climates. During the master planning of neighbourhoods, design decisions related to the urban layout and geometry can affect the availability of solar radiation considerably. Different studies focussing on the urban morphology and its impact on building compactness, access to sunlight, daylight and natural ventilation suggest that optimizing the urban texture can lead to a reduction in energy use by a factor 2 (Ratti, Baker, & Steemers, 2005) (Salat, 2009). However, the impact of urban planning decisions on the energy consumption is often neglected because of the lack of appropriate energy simulation tools (Ratti et al., 2005).

Different calculation methods are available to estimate the availability of solar gains in buildings. In the Flemish Energy Performance of Buildings (EPB) regulation (Flemish Government, 2005), the impact of the built environment is simplified by defining a set of obstruction angles per window. This method however lacks accuracy to analyse the influence of the urban geometry and shading caused by neighbouring buildings (Trigaux, Allacker, & De Troyer, 2014). Other methods, considering the real obstructions, such as in the energy simulation software EnergyPlus (U.S Department of Energy, n.d.), are often too complex and require a lot of input data, which are not available in the urban planning phase.

With the development of Building Information Modelling, the use of 3D environments to retrieve input data for energy calculations is increasing. An example is OpenStudio, linking a 3D Sketchup model with EnergyPlus (U.S. Department of Energy, n.d.). This approach is used by different researchers. In (Ratti et al., 2005), data related to the urban geometry are extracted from digital elevation models of cities and used as input for energy calculations. In (Weytjens, 2013) a plugin is developed to link a 3D SketchUp building model (Trimble, n.d.) with an energy analysis based on the Flemish EPB regulation. The latter is particularly adapted for the early design stage, but the calculation of solar gains is simplified by using a fixed reduction factor for shading obstructions. In this paper, the possibility of extracting detailed data on solar obstructions from a SketchUp neighbourhood model is investigated.

2. Research objectives

The objective of this research is to develop an accurate design tool to optimise solar gains and energy use during the planning phase of neighbourhoods, which requires limited input. The global structure of this tool is illustrated in Fig 1. Based on a SketchUp 3D neighbourhood model, detailed information on solar obstructions is extracted by means of a plugin. This information can then be visualised on sun-path diagrams and linked to solar gain calculations. In this paper, solar gains are calculated based on a refinement of the existing Flemish EPB method, further referred to as EPB+ method. Finally, the data regarding solar gains are used as input for the calculation of the neighbourhood energy consumption, based on the dynamic Equivalent Degree Day (EDD) method (Trigaux et al., 2014).

In the subsequent section the methodology is described, focussing on the solar gain calculations and the dynamic EDD method. In section 4 the developed tool is used to analyse a parametric neighbourhood model. Conclusions are formulated in the final section.

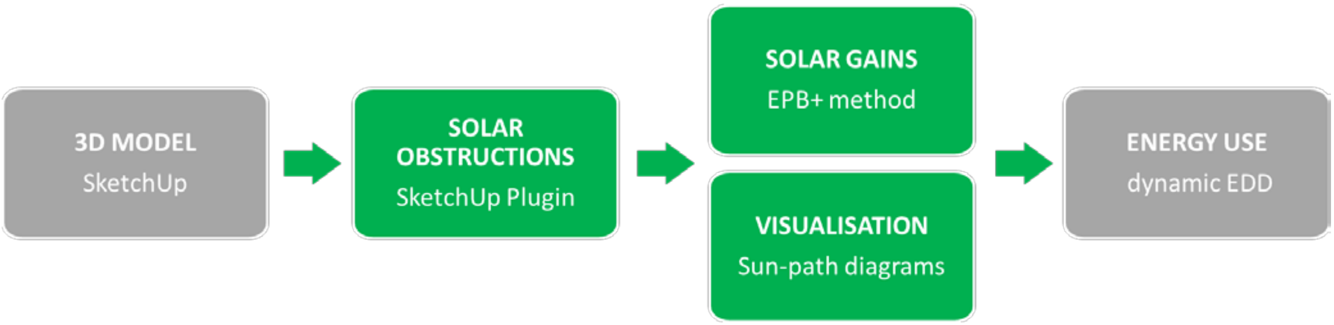


Fig 1 : Structure of the developed design tool. The focus of this research, including the extraction of data on solar obstructions from a 3D environment is indicated in green.

3. Method

3.1 EPB method for solar gain calculations

Solar gains in the existing EPB method are defined as the sum of the direct, diffuse and reflected solar gains. The incident direct solar radiation per month on an unshaded surface j ($I_{s,dir,m,j,unshad}$) is estimated based on a characteristic day for each month, using Formula 1 (Flemish Government, 2005):

$$I_{s,dir,m,j,unshad} = I_{s,dir,m,hor} * \frac{Q_{s,dir,char,j}}{Q_{s,dir,char,hor}} \quad (1)$$

With:

- $I_{s,dir,m,hor}$ = direct solar radiation per month on an unshaded horizontal surface, based on registrations (MJ/m²).
- $Q_{s,dir,char,j}$ = calculated direct solar radiation on an unshaded surface j with given orientation, for the characteristic day of the analysed month (J/m²day)
- $Q_{s,dir,char,hor}$ = calculated direct solar radiation on an unshaded horizontal surface for the characteristic day of the analysed month (J/m²day)

For each characteristic day, the direct solar radiation is calculated, taking into account the sun incidence angle hour by hour.

The incident diffuse solar radiation per month on an unshaded surface j ($I_{s,dif,m,j,unshad}$) is proportional to the visible part of the sky dome (sky view factor) and estimated based on Formula 2 (Flemish Government, 2005):

$$I_{s,dif,m,j,unshad} = I_{s,dif,m,hor} * C_m * \frac{1+\cos\theta_j}{2} \quad (2)$$

With:

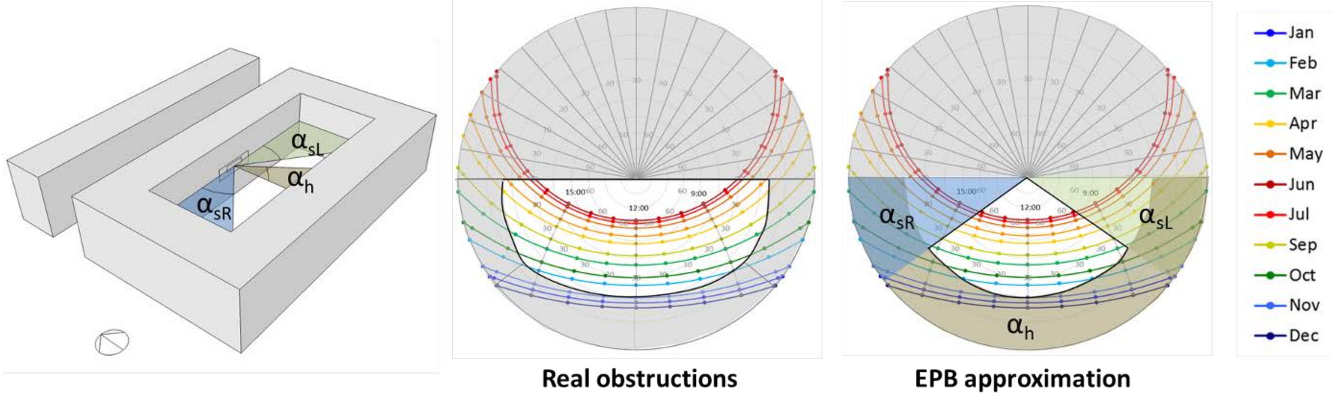
- $I_{s,dif,m,hor}$ = diffuse solar radiation per month on an unshaded horizontal surface, based on registrations(MJ/m²)
- C_m = correction factor for the anisotropic character of the diffuse solar radiation
- θ_j = surface inclination compared to a horizontal surface (°)

For the reflected solar radiation, only reflections from the ground are considered. The incident reflected solar radiation per month on an unshaded surface j ($I_{s,refl,m,j,unshad}$) is proportional to the visible part of the ground (ground view factor) and the ground surface reflectance, for which a default value of 0.2 is used, according to Formula 3 (Flemish Government, 2005):

$$I_{s,dif,m,j,unshad} = 0.2 * I_{s,tot,m,hor} * \frac{1-\cos\theta_j}{2} \quad (3)$$

With:

- $I_{s,tot,m,hor}$ = total solar radiation per month on an unshaded horizontal surface, based on registrations (MJ/m²)
- θ_j = surface inclination compared to a horizontal surface (°)



Real obstructions **EPB approximation**

Fig 2: Stereographic projection of solar obstructions for a window in a rectangular urban block (solar trajectories for Belgium: 51°N). Real obstructions (left) are compared with the EPB approximation (right) (Trigaux et al., 2014)

In the EPB method the impact of shading patterns, resulting from neighbouring buildings, trees, sheds or side walls, is simplified by defining a set of obstruction and overhang angles per window. For each window those angles are then projected on the visible part of the sky dome to calculate the reduction in direct and diffuse solar radiation, compared to unshaded conditions (Trigaux et al., 2014). Concerning the reflected solar radiation, the impact of shadowing on the ground, reducing ground solar reflection, is not considered. The amount of reflected solar radiation is thus identical in unshaded and shaded conditions. This is further discussed in Section 4. As illustrated in Fig 2 for a dwelling in a rectangular urban block, the EPB approximation can lead to an overestimation of shading patterns and hence to an underestimation of solar gains (Trigaux et al., 2014). A refined EPB+ method is proposed to tackle this issue.

3.2 EPB+ method for solar gain calculations

The EPB+ method is based on detailed data on solar obstructions, which are extracted from a SkechUp 3D model, by means of a plugin. The plugin consists of three functions. The first two are used for analysing respectively the direct and diffuse solar radiation. The third function provides data for the visualisation of solar obstructions on sun-path diagrams. The analysis of the direct solar radiation is illustrated in Fig 3. For each characteristic day of each month, rays are drawn, hour by hour, starting from the analysed window and pointing to the sun. When rays intersect with the 3D model, there is no direct solar gain. The analytical outcome is a matrix, indicating the availability of direct solar radiation hour by hour for each characteristic day. This matrix is used as input for the calculation of the incident direct solar radiation on the analysed window.

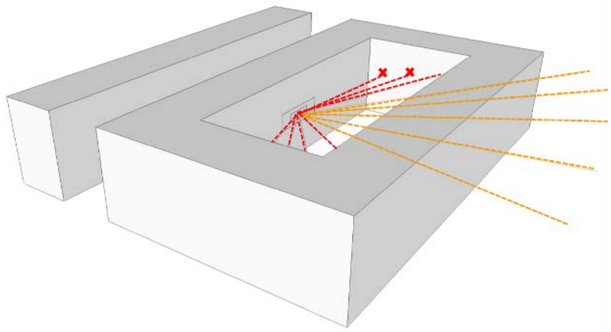


Fig 3: Analysis of the direct solar radiation based on the SketchUp plugin. Rays intersecting with the 3D model (red lines) correspond to hours without direct solar gains

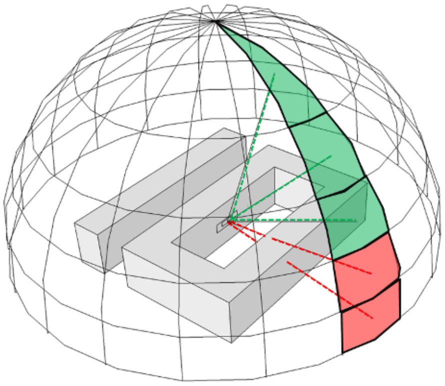


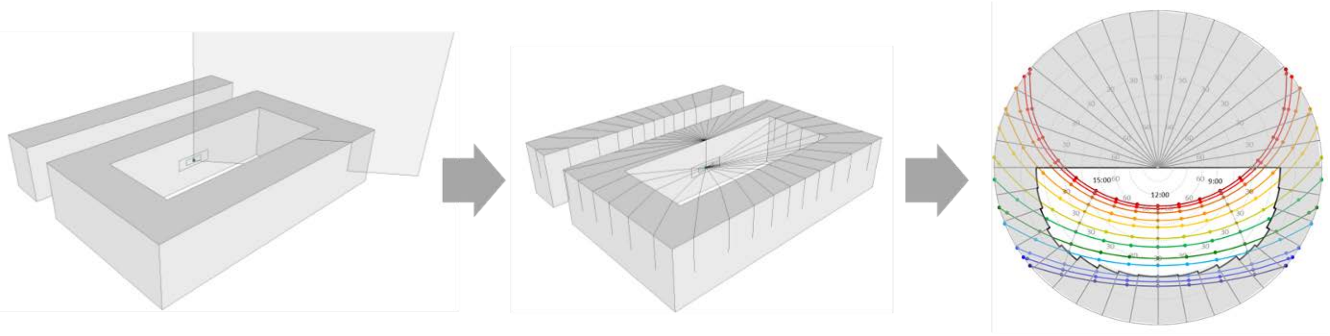
Fig 4: Calculation of the sky view factor using the SketchUp plugin. Green and red surfaces represent respectively the visible and invisible part of the sky dome from the centre of the window.

As mentioned in section 3, the amount of diffuse solar radiation is proportional to the sky view factor. To estimate the effect of solar obstructions, the sky dome is subdivided in x surfaces with equal area (Fig 4). For each surface, a ray is drawn between the surface centre and the window. The sky view factor is then calculated as the number of non-intersecting rays divided by the total number of analysed rays. The calculation accuracy can be increased by reducing the size of the analysed surfaces. In this paper, a subdivision in 3600 equal surfaces is used for simulations, leading to very accurate results.

Finally, data on solar obstructions can be extracted for visualisations from the model, by drawing vertical planes through the centre of the analysed window, in 36 directions, in steps of 10° (Fig 5). Obstruction angles are derived based on the intersection lines with the 3D model. Via those angles the programme visualises obstructions on sun-path diagrams.

3.3 Dynamic Equivalent Degree Day (EDD) method

The dynamic EDD method is a simplified approach, to estimate the heating energy demand in buildings, taking into account the building layout and shading caused by interacting buildings (Trigaux et al., 2014). Compared to the existing EDD method (Diensten voor de programmatie van het wetenschapsbeleid, 1984), this approach proposes a more accurate estimation of the impact of solar gains by including results from semi-dynamic (e.g. EPB method) or dynamic solar gain calculations. Because of the limited number of input data, this method is very useful for the early design stages. In our approach solar gain output from the EPB+ method is used as input for the dynamic EDD method in order to simulate the heating energy consumption in neighbourhoods. A more detailed description of the dynamic EDD method can be found in (Trigaux et al., 2014).



Intersection planes **Obstruction angles** **Visualisation**

Fig 5: Extraction of data on solar obstructions, based on the SketchUp plugin. The data are used for visualisations on sun-path diagrams.

4. Results

4.1 Neighbourhood model

To illustrate the methodology a parametric neighbourhood model of rectangular urban blocks is defined (Fig 6) (Trigaux et al., 2014). In order to evaluate the impact of shading interactions, we focus on a medium-density urban block, consisting of 15m high buildings surrounding a courtyard of 50m by 20m. For the simulations, the urban block is subdivided in a grid of dwellings of 100m². Glazed surfaces are assumed to be 25% of the façades and are approximated by a big window in each façade of each housing unit. Concerning the insulation level, a building envelope, in line with the low energy standard, is used for the calculations.

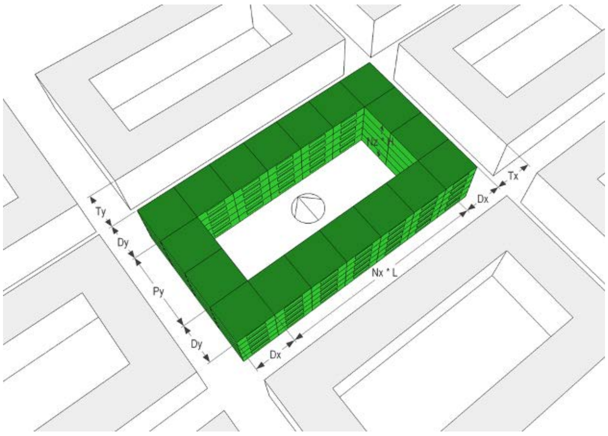
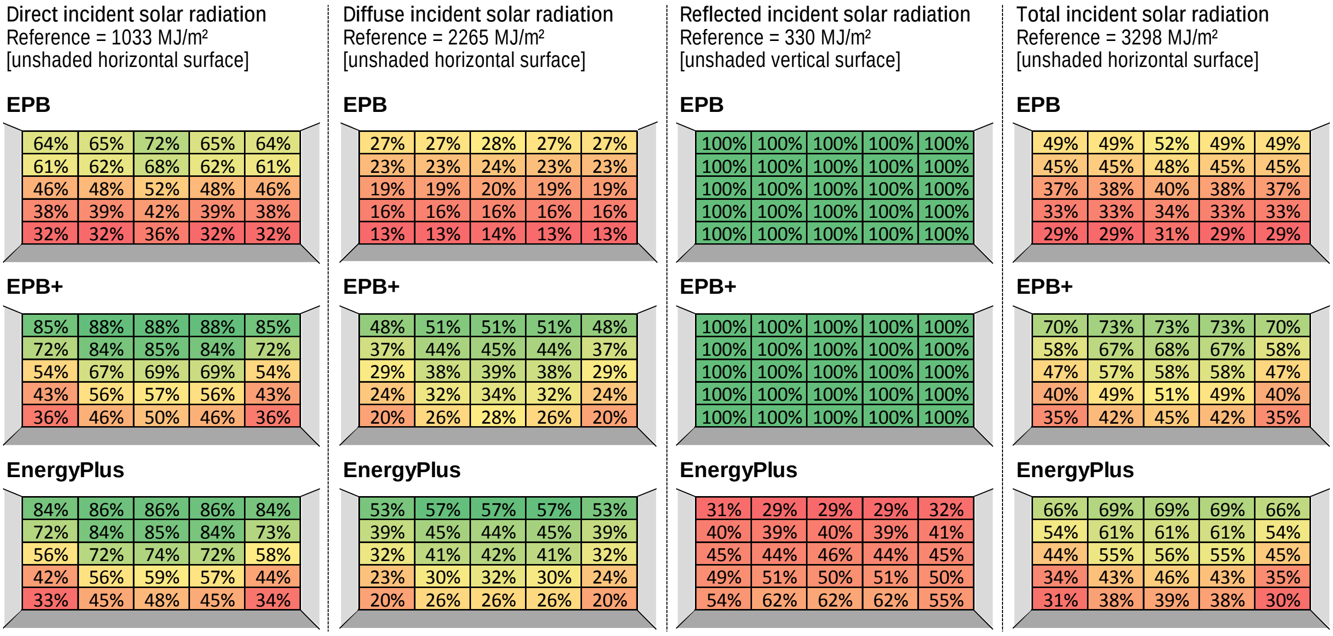


Fig 6: Parametric neighbourhood model

4.2 Solar gain calculations

To validate the methodology, solar gains are calculated for all windows of the courtyard façades. The direct, diffuse and reflected incident solar radiation is estimated based on the EPB and EPB+ method and compared with EnergyPlus simulations using the “Full Exterior With Reflections” solar distribution, which includes detailed reflection calculations. For the comparison, the same climate data, based on the EnergyPlus weather file for Brussels, are used as input for the three calculation methods, which slightly differ from the monthly values in the EPB regulation. The results for the south-oriented courtyard façade are shown in Fig 7 and expressed in percentage compared to a reference. For the direct, diffuse and total radiation, an unshaded horizontal surface is used as reference. For the reflected radiation, the reference is the amount of ground reflected radiation on a vertical surface, excluding the impact of shadowing on the ground.

Concerning the direct and diffuse solar radiation, the results show a good agreement between the EPB+ and EnergyPlus calculations with positive and negative differences limited to about 5%. The EPB+ method is hence much more accurate than the EPB method, which in this case systematically overestimates the impact of shading, with differences up to 30%, compared to EnergyPlus. The reflected solar radiation shows much lower values from EnergyPlus, compared to EPB and EPB+. This is a result of the simplified calculation of ground reflected radiations in EPB and EPB+, excluding the effects of shadowing of buildings on the ground. However, due to the limited contribution of reflected radiation to the total solar gains, this overestimation has only a limited impact on the results for the total incident solar radiation with differences limited to 7% between EPB+ and EnergyPlus. The results for the other façades are not discussed in this paper but similar conclusions can be drawn concerning the good agreement between EPB+ and EnergyPlus.



Direct incident solar radiation
Reference = 1033 MJ/m²
[unshaded horizontal surface]

EPB

64%	65%	72%	65%	64%
61%	62%	68%	62%	61%
46%	48%	52%	48%	46%
38%	39%	42%	39%	38%
32%	32%	36%	32%	32%

EPB+

85%	88%	88%	88%	85%
72%	84%	85%	84%	72%
54%	67%	69%	69%	54%
43%	56%	57%	56%	43%
36%	46%	50%	46%	36%

EnergyPlus

84%	86%	86%	86%	84%
72%	84%	85%	84%	73%
56%	72%	74%	72%	58%
42%	56%	59%	57%	44%
33%	45%	48%	45%	34%

Diffuse incident solar radiation
Reference = 2265 MJ/m²
[unshaded horizontal surface]

EPB

27%	27%	28%	27%	27%
23%	23%	24%	23%	23%
19%	19%	20%	19%	19%
16%	16%	16%	16%	16%
13%	13%	14%	13%	13%

EPB+

48%	51%	51%	51%	48%
37%	44%	45%	44%	37%
29%	38%	39%	38%	29%
24%	32%	34%	32%	24%
20%	26%	28%	26%	20%

EnergyPlus

53%	57%	57%	57%	53%
39%	45%	44%	45%	39%
32%	41%	42%	41%	32%
23%	30%	32%	30%	24%
20%	26%	26%	26%	20%

Reflected incident solar radiation
Reference = 330 MJ/m²
[unshaded vertical surface]

EPB

100%	100%	100%	100%	100%
100%	100%	100%	100%	100%
100%	100%	100%	100%	100%
100%	100%	100%	100%	100%
100%	100%	100%	100%	100%

EPB+

100%	100%	100%	100%	100%
100%	100%	100%	100%	100%
100%	100%	100%	100%	100%
100%	100%	100%	100%	100%
100%	100%	100%	100%	100%

EnergyPlus

31%	29%	29%	29%	32%
40%	39%	40%	39%	41%
45%	44%	46%	44%	45%
49%	51%	50%	51%	50%
54%	62%	62%	62%	55%

Total incident solar radiation
Reference = 3298 MJ/m²
[unshaded horizontal surface]

EPB

49%	49%	52%	49%	49%
45%	45%	48%	45%	45%
37%	38%	40%	38%	37%
33%	33%	34%	33%	33%
29%	29%	31%	29%	29%

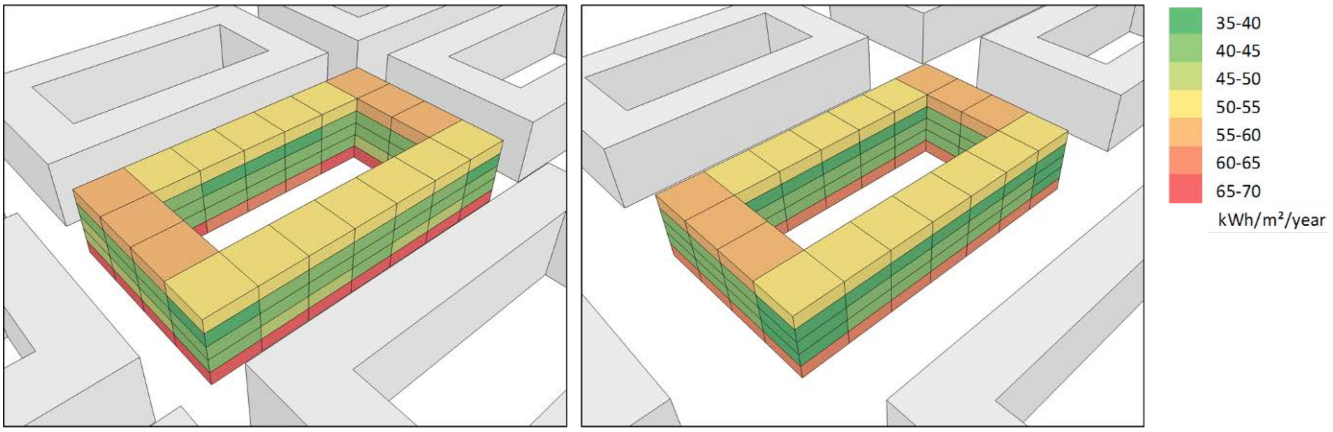
EPB+

70%	73%	73%	73%	70%
58%	67%	68%	67%	58%
47%	57%	58%	58%	47%
40%	49%	51%	49%	40%
35%	42%	45%	42%	35%

EnergyPlus

66%	69%	69%	69%	66%
54%	61%	61%	61%	54%
44%	56%	56%	55%	45%
34%	43%	46%	43%	35%
31%	38%	39%	38%	30%

Fig 7: Direct, diffuse, reflected and total solar radiation on the south-oriented windows in the courtyard, based on EPB, EPB+ and EnergyPlus. The results are projected on the façade and expressed in percentage, compared to a reference.



Model 1 - 10 m wide streets

Model 2 - 20m wide streets

Fig 8: Heating energy demand in two neighbourhood models with streets of 10m wide (model 1) and 20m wide (model 2)

4.3 Heating energy demand calculations

Based on the solar gain output from the EPB+ method, the heating energy demand in the housing units of the urban building block is estimated, using the dynamic EDD method. To illustrate the approach, two variants of the neighbourhood model are evaluated: one with 10m wide streets (model 1) and one with 20m wide streets (model 2) (Fig 8). In each model, differences in heating energy demand, up to about 30kWh/m²/year, between different housing units, are found, depending on their position in the building block. Dwellings under the roof and on the ground floor have a much higher energy demand due to higher heat transmission losses through the roof or floor on grade. Furthermore, housing units with identical orientation and heat loss surfaces, show a higher energy demand, when located on lower floors and/or close to the courtyard corners, because of the reduced availability of solar radiation.

Compared to model 1, the average heating energy demand of the dwellings in model 2 is about 3.5% lower. The reduction is relatively limited because the increased street width has only a strong effect on some housing units. The biggest differences, going up to about 5kWh/m²/year, are noticed for the dwellings with a south-oriented street façade, which in model 2 can benefit much more from the available solar radiation.

5. Conclusions

In this paper a design tool is developed to optimise solar gains and energy use during the master planning phase of neighbourhoods. The existing EPB method for solar gain calculations is refined, using data on solar obstructions, extracted from a 3D SketchUp model. Solar gain calculations of a medium-density urban block show a good level of correspondence between the proposed method and dynamic simulations, based on EnergyPlus. Furthermore, by linking the EPB+ method to the dynamic EDD method, the impact of urban planning decisions on the neighbourhood heating energy consumption can be estimated accurately, with a limited number of input data.

For further research, we recommend validating the design tool, based on a larger number of case studies. Furthermore it should be investigated if a similar approach can be used to estimate the availability of daylight in neighbourhoods and its impact on the lighting energy consumption in buildings.

6. References

Flemish Government. Besluit van de Vlaamse Regering van 11 maart 2005 tot vaststelling van de eisen op het vlak van de energieprestaties en het binneklimaat van gebouwen - bijlage I (2005).

Ratti, C., Baker, N., & Steemers, K. (2005). Energy consumption and urban texture. Energy and Buildings, 37(7), 762–776. http://doi.org/10.1016/j.enbuild.2004.10.010

Salat, S. (2009). Energy loads, CO 2 emissions and building stocks: morphologies, typologies, energy systems and behaviour. Building Research & Information, 37(5-6), 598–609. http://doi.org/10.1080/09613210903162126

Trigaux, D., Allacker, K., & De Troyer, F. (2014). A simplified Approach to integrate Energy Calculations in the Life Cycle Assessment of Neighbourhoods. In Sustainable habitat for developing societies (pp. 55–55). Ahmedabad, India: CEPT University Press.

Trimble. (n.d.). SketchUp. Retrieved May 2, 2015, from www.sketchup.com

U.S Department of Energy. (n.d.). EnergyPlus Energy Simulation Software. Retrieved January 9, 2014, from http://apps1.eere.energy.gov/buildings/energyplus/

U.S. Department of Energy. (n.d.). OpenStudio. Retrieved May 1, 2015, from www.openstudio.net

Weytjens, L. (2013). Design support for energy efficiency and summer comfort of dwellings in early design phases: A framework for a design tool adapted to the architects' practice in Flanders (PhD dissertation). Universiteit Hasselt, Hasselt.