GENERATIVE DESIGN FOR A SUSTAINABLE URBAN MORPHOLOGY

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Abstract
The present work concerns the applications of generative design for sustainable urban fabric. This represents an iterative process that involves an algorithm for the generation of solar envelopes to satisfy solar and density constraints. We propose in this paper to explore a meta-universe of human-machine interaction. It aims to design urban forms that offer solar access. This being to minimize heating energy expenditure and provide solar well-being. We propose to study the impact of the solar strategy of building morphosis on energy exposure. It consists of determining the layout and shape of the constructions based on the shading cut-off time. This is a period of desirable solar access. We propose to define it as a balance between the solar irradiation received in winter and that received in summer. We rely on the concept of the solar envelope defined since the 1970s by Knowles and its many derivatives (Koubaa Turki & al., 2020). We propose a parametric model to generate solar envelopes at the scale of an urban block. The generative design makes it possible to create a digital model of the different density solutions by varying the solar access duration. The virtual environment created allows exploring urban morphologies resilient both to urban densification and better use of the context’s resources. The seasonal energy balance, between overexposure in summer and access to the sun in winter, allows reaching high energy and environmental efficiency of the buildings. We have developed an algorithm on Dynamo for the generation of the solar envelope by shading exchange. The program makes it possible to detect the boundaries of the parcels imported from Revit, establish the layout of the building, and generate the solar envelopes for each variation of the shading cut-off time. It also calculates the FAR[1] and the FSI[2] from the variation of the shading cut-off time for each parcel of the island. We compare the solutions generated according to the urban density coefficients and the solar access duration. Once the optimal solution has been determined, we export the results back into Revit environment to complete the BIM modelling for solar study. This article proposes a method for designing buildings and neighbourhoods in a virtual environment. The latter acts upstream of the design process and can be extended to the different phases of the building life cycle: detailed design, construction, and use.

Keywords
Solar envelope, Smart virtual environment, Seasonal energy balance, Urban morphology, Generative Design.

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ABSTRACT
The present work concerns the applications of generative design for sustainable urban fabric. This represents an iterative process that involves an algorithm for the generation of solar envelopes to satisfy solar and density constraints. We propose in this paper to explore a meta-universe of human-machine interaction. It aims to design urban forms that offer solar access. This being to minimize heating energy expenditure and provide solar well-being. We propose to study the impact of the solar strategy of building morphosis on energy exposure. It consists of determining the layout and shape of the constructions based on the shading cut-off time. This is a period of desirable solar access. We propose to define it as a balance between the solar irradiation received in winter and that received in summer. We rely on the concept of the solar envelope defined since the 1970s by Knowles and its many derivatives (Koubaa Turki & al., 2020). We propose a parametric model to generate solar envelopes at the scale of an urban block. The generative design makes it possible to create a digital model of the different density solutions by varying the solar access duration. The virtual environment created allows exploring urban morphologies resilient both to urban densification and better use of the context’s resources. The seasonal energy balance, between overexposure in summer and access to the sun in winter, allows reaching high energy and environmental efficiency of the buildings. We have developed an algorithm on Dynamo for the generation of the solar envelope by shading exchange. The program makes it possible to detect the boundaries of the parcels imported from Revit, establish the layout of the building, and generate the solar envelopes for each variation of the shading cut-off time. It also calculates the FAR and the FSI from the variation of the shading cut-off time for each parcel of the island. We compare the solutions generated according to the urban density coefficients and the solar access duration. Once the optimal solution has been determined, we export the results back into Revit environment to complete the BIM modelling for solar study. This article proposes a method for designing buildings and neighbourhoods in a virtual environment. The latter acts upstream of the design process and can be extended to the different phases of the building life cycle: detailed design, construction, and use.

Keywords: Solar envelope, Smart virtual environment, Seasonal energy balance, Urban morphology, Generative Design.

1 Floor Space Area is the ratio between the sum of the floor’s areas and the plot area.
2 Floor Space Index is a floor occupation coefficient corresponding to the ratio between the buildable floor area and the plot area.
ملخص

يقدم هذا البحث تطبيقات لتصميم توليدي للنسج الحضري المستدام. ويتضمن خوارزمية لتوليد الغلافات الشمسية لتلبية متطلبات التقاط الطاقة الشمسية والكثافة الحضرية. تقترح في هذا البحث استكشاف تأثير التفاعل بين الإنسان والأثر بهدف تصميم الأشكال الحضرية التي يمكن من التقاط الطاقة الشمسية لتقليل نفقات الطاقة الحرارية وزيادة الرفاهية للإنسان. نقترح دراسة استراتيجية لتشكل المبنى حسب تعرض للطاقة الشمسية وذلك بتخطيط وشكل الإنشاءات بناء على وقت إيقاف التظليل وهو فترة التقاط الطاقة الشمسية المرغوب فيها. إذ أن هذه الفترة الزمنية مستندة على نواز بين أوقات الطاقة الشمسية المتقطعة في الشتاء وفي الصيف. نعتمد على مفهوم الغلاف الشمسي المقترح منذ السبعينيات من قبل رالف نولز ومشتركته الجديدة (قوبعة التركي وأخرون، 2020). نقترح نموذجا برامجيا لتوليد غلافات شمسية ضمن الكثافة الحضرية. يتيح التصميم التوليدي إمكانية إنشاء نموذج رقمي لمختلف حلول الكثافة الحضرية من خلالigue مدة إيقاف التظليل. تسمح البيئة الافتراضية التي تم إنشاؤها بتشكيل الأشكال الحضرية التي تتم إبداع التكثيف الحضري والاستخدام الأفضل للموارد المتاحة. يتيح توزر الطاقة الموسمية، بين اجتناب التعرض المفرط لأشعة الشمس في الصيف والرغبة فيها في الشتاء، الوصول إلى جودة طاقة عالية وكفاءة بينية للمبنى. لقد اقترحنا خوارزمية لتوليد الغلافات الشمسية عن طريق تبادل التظليل عبر برامج دينامو. تمكنا الخوارزمية من تشكيل المبتليات الافتراضية على شكل مغلفات شمسية وذلك حسب إيقاف التظليل. وقد قمنا بتضخيم الحلول حسب معايير الكثافة الحضرية وعدد الفائدة الطاقة الشمسية. بمجرد تحميل الحل الأول، تقوم بمصدر الناتج إلى برنامج ريغي لإكمال التصميم. تطور هذه المقالة طريقة جديدة لتصميم نمذجة المباني والحواجز في بيئة افتراضية. تدرج هذه البرمجية في بداية عملية التصميم ويمكن أن تمتد إلى المراحل المختلفة من دورة حياة المبنى: التصميم الفضائي والبناء والاستخدام.

الكلمات المفتاحية: الغلاف الشمسي، البيئة الافتراضية الذكية، توزر الطاقة الموسمية، التشكيل الحضري، التصميم التوليدي.
1. PROBLEMATIC AND APPROACH

The solar rights appeared in the late 1970s through the concept of the solar envelope described by Knowles between 1968 and 1971 (Knowles, 1974, 1980). This morphological concept guarantees this right by allowing solar access to a building without shading its neighbours at specific times. These times, called the cut-off-time, define the period for which solar access is desirable. Shadows are inscribed within a virtual spatial boundary, called the shadow fence, which defines the shadow projection boundary of the massing. The cut-off time and the shadow fences are the two constraints of morphological definition of the solar envelope. Koubaa Turki and al. (2020) have drawn up the state of the art of the various works relating to the determination of these two constraints. Until 2020, the works on determining these constraints represent 15% of publications on the solar envelope, 60% of which are dedicated to the study of cut-off time and 40% to the study of shadow closure.

We have noticed an interest in determining the cut-off time maximizing solar gain in winter (Capeluto & Plotnikov, 2017; Knowles, 1981; Morello & Ratti, 2009). On the other hand, few studies propose studying both winter and summer energy gain (Raboudi & Ben Saci, 2014; Vartholomaios, 2015). With global overheating, the impact of solar gains in summer is increasingly important. Indeed, air conditioning often becomes necessary for spaces with high solar gain in summer. That is why we propose the notion of seasonal energy balance of contributions between winter and summer, considering neighbouring buildings. The objective is to propose a method for designing virtual morphologies that ensure a compromise between desirable solar irradiation in winter and undesirable one in summer.

2. DETERMINATION OF THE CUT-OFF TIME

2.1. Determination of the Cut-Off Time in the State of the Art

The cut-off time is determined, initially, according to the periods of useful insolation or solar energy collection. Knowles (1981) proposed to calculate the useful periods of solar access by weighting the incident solar radiation at several times of the day, by the sinus of the angle of the sun altitude. We have listed several research studies about cut-off time determination research; depending on periods of useful insolation (1981), received solar gains (Vartholomaios, 2015) and depending on energy consumption (Bruce, 2008). The cut-off time was also determined according to the thermal comfort of the exterior space (Sorayaei & Sorayaei, 2017) or that of the interior space (Capeluto & Plotnikov, 2017). Three quarters of the studies determining the cut-off time relate to solar collection. Indeed, advances in energy calculation models, in particular Radiance (Ward, 1994) and Energyplus (Crawley et al., 2001) have made it possible to refine the determination of the cut-off time according to energy capture (Capeluto et al., 2006; Capeluto & Plotnikov, 2017; Koubaa Turki et al., 2018; Raboudi & Ben Saci, 2014; Vartholomaios, 2015).

Most cut-off time determination studies focus on desirable solar access in winter. However, this period corresponds to overheating hours in summer. Niemasz et al. (2013) studied the application of the solar envelope on land located in seven cities in North America. The authors evaluated the energy consumption of these envelopes. They noticed that this model has an advantage on energy consumption for heating against a considerable deficit for climates requiring cooling loads.

Hence the question: What would be the optimal solar access period in winter and summer and not only during the winter period?

We propose, in this research, to maximize the direct solar irradiation received in winter and to minimize the direct solar irradiation received in summer. The model proposes a virtual environment of urban morphologies resilient both to urban densification and solar access.
2.2. Method for Delimiting the Shading Cut-Off Time

We define, for a given place, the shading cut-off time (denoted $T_0$) by calculating the sum of the direct solar irradiation in winter (denoted $R_{dh}$) and the sum of them in summer (denoted $R_{de}$) received per hour on 1m² of vertical surface. We calculate these irradiations in winter and summer by different orientations of facades with a rotation step of 22.5°.

We are interested in a solar neighbourhood approach to maximize the capture of direct solar irradiance in winter and minimize it in summer.

We calculate the direct solar irradiation received during the winter per hour from sunrise to sunset on the different orientations. We refer to the Pareto principle (1967) to define the retained time-period. We propose that the time-period retained in winter be around 20% of the hours of the day which corresponds to at least 80% of the total irradiation. We are looking for the time slot that provides this percentage of daily solar gain in winter for all orientations such as:

$$\sum R_{dh} \, T_0 \geq 80\% \sum R_{dh} \text{ daily for the winter} \quad (1)$$

We calculate the direct solar irradiation received on the different orientations in summer during the time slots satisfying this condition in winter.

We propose the energy balance factor, (denoted $Q$), which characterizes the ratio of these two irradiations and qualifies the relationship of the direct solar irradiation received in winter and in summer. It is calculated by the ratio between the sum of the direct solar irradiation received in winter and that received in summer. We consider a range of shading cut-off times satisfying the previous condition with:

$$Q = \frac{\sum R_{dh} \, T_0}{\sum R_{de} \, t_i} \text{ such that } \sum R_{dh} \, T_0 \geq 80\% \sum \text{ Daily } R_{dh} \quad (2)$$

We choose the shading cut-off time which has a maximum coefficient corresponding to a high solar irradiation rate in winter and a low one in summer.

3. EXPERIMENTATION AND RESULTS

We present an application example on an urban block of three plots (A, B and C) located in Lac of Tunis (Figure 1).

![Satellite photo of the urban block composed of three plots A, B and C located at the Lac of Tunis](https://digitalcommons.bau.edu.lb/apj/vol28/iss3/15)
3.1. Determining the Shading Cut-Off Time for Tunis

We define the shading cut-off time by calculating the sum of the direct solar irradiation received per hour on 1m² of vertical surface in winter (from 21 December to 21 March) and summer (from 21 June to 21 September) by different orientations of facades with a rotation step of 22.5°. Then, we deduce the hourly percentage compared to the daily sum in the two seasons (Figure 2).

![Fig.2: Percentages of direct solar irradiation received in winter and in summer on one square meter of facade for different orientations with a step of 22.5° in Tunis compared to the daily sum (in kWh/m²).](image)

We observe that, from 7:00 to 9:00, and from 16:00 to 18:00, direct solar irradiation is negligible compared to the total irradiation in winter. The cumulative percentage of irradiation from 10:00 to 15:00 is 83.2% compared to the total sum of the irradiance received in winter.

Then, we calculate the cumulative sum of solar irradiation received for several ranges of shading cut-off times in winter and the corresponding cumulative sum in summer. We deduce the percentages from the daily sum and the energy balance factor Q (Figure 3).

The cumulative percentage of irradiation (Figure 3) from 10:00 to 15:00 is 43.75% compared to the total amount of irradiation received in summer. This led to fixing the shading cut-off time $T_o = [10:00, 15:00]$. This duration corresponds to 25% of the day’s hours. For this period, the Q is 0.56. This is the maximum ratio satisfying the required condition of solar access in winter and corresponding to the minimum solar gain in summer.

![Fig.3: Percentage of cumulative values of solar irradiation per cut off time.](image)

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3 With Insight in Revit for energy simulation using DOE 2.2 and EnergyPlus.
3.2. Generation of Solar Envelopes

We propose a workflow based on Revit environment. We use Dynamo for parametric algorithm that we be involved on generative design by Refinery. The selected solution is exported to Revit for solar analysis.

The generative design makes it possible to study the different urban density solutions by varying the shading cut-off time. We have developed an algorithm on Dynamo (Figure 5) for the generation of the solar envelope by shading exchange using Boolean operations (Stasinopoulos, 2000). The program makes it possible to detect the boundaries of the parcels imported from Revit, to determine the layout of the building and the generation of the solar envelope for each variation of cut-off time. So, we can deduce the maximum height of the buildings that ensure the solar access conditions. It also calculates the FAR and the FSI from the variation of the cut-off time for each parcel of the island.

Finally, we compare the solutions generated according to the urban density coefficients (FSI and FAR) and the solar access duration.

The inputs are the location of the site, a start time cursor t1 and an end time cursor t2 of the shading cut-off time interval [10:00,15:00]. The output results are the FAR and FSI urban density indices and the shading cut-off time duration.

Fig.4: Workflow of BIM, Parametric modelling, Generative Design study and Solar analysis.

Fig.5: Dynamo solar envelope component.
The cross product on Refinery (Di Filippo et al., 2021) makes it possible to obtain 21 variants for each plot (Figure 6). The multidimensional representation below allows us to see the implications for all the variables considered.

![Parameters diagrams of solutions obtained for each plot (A, B, C) corresponding to the various urban density of shading cut-off time.](image)

We examine the results by two studies where the goals are to (1) maximize the FAR and (2) maximize the solar access duration (Figure 7).

![Simulation of results in real context for (a) maximum FAR and (b) maximum duration.](image)

Firstly, we propose to study the best solution that maximizes the FAR for each plot (Table 1).

**Table 1. Results for a maximum FAR and a minimum 3 hours duration of cut-off time for the three plots.**

<table>
<thead>
<tr>
<th></th>
<th>Plot A</th>
<th>Plot B</th>
<th>Plot C</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSI</td>
<td>0.827</td>
<td>0.515</td>
<td>0.892</td>
</tr>
<tr>
<td>FAR</td>
<td>3.732</td>
<td>3.251</td>
<td>1.617</td>
</tr>
<tr>
<td>Duration</td>
<td>3</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Cut-off time</td>
<td>[10:00h,12:00]</td>
<td>[11:00,15:00]</td>
<td>12:00</td>
</tr>
</tbody>
</table>
For the goal of maximum FAR, plot A has the best result with a gain of 12.8% and 56.67% compared to respectively plot B and plot C.

Secondly, we propose the goal of having a maximum duration of cut-off time for the three plots (Table2).

<table>
<thead>
<tr>
<th>Plot</th>
<th>FSI</th>
<th>FAR</th>
<th>Duration</th>
<th>Cut-off time</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.55</td>
<td>1.928</td>
<td>6</td>
<td>[10:00,15:00]</td>
</tr>
<tr>
<td>B</td>
<td>0.473</td>
<td>2.473</td>
<td>6</td>
<td>[10:00,15:00]</td>
</tr>
<tr>
<td>C</td>
<td>0.503</td>
<td>1.223</td>
<td>6</td>
<td>[10:00,15:00]</td>
</tr>
</tbody>
</table>

Plot B can guarantee a better FAR with a gain of 22.08% and 50.54 % compared to respectively plot A and plot C.

So, we can have a range of optimal solutions satisfying the two previous conditions. Figure 8 represents the three diagrams relating to the three plots that represent optimal solutions relating urban density and solar access constraints. We represent on the x axis the solar access duration, on the y axis the FAR and in colour variation for the FAR.

![Fig.8: Optimal solutions for maximum FAR and maximum duration.](https://digitalcommons.bau.edu.lb/apj/vol28/iss3/15)
4. DISCUSSION

This paper proposes a resilient approach to optimize urban density and solar access by studying the optimal duration and FAR. It proposes a method for determining urban morphology by controlling the solar access duration. Varying the period of the shading cut-off time makes it possible to explore different urban densities (Figure 9) while guaranteeing solar access over a useful solar access time slot.

The aim of this approach is to exploit the solar morphological potential of each plot. The position, shape and size of the plot impact the FAR and the solar access duration. The study of the maximum FAR and the duration of solar access makes it possible to obtain the best solutions for each plot. The multi-objective approach would be necessary in this case.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSI</td>
<td>0.827</td>
<td>0.515</td>
<td>0.392</td>
</tr>
<tr>
<td>FAR</td>
<td>2.732</td>
<td>3.251</td>
<td>1.617</td>
</tr>
<tr>
<td>DURÉE</td>
<td>3</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>To</td>
<td>[10.00,12.00]</td>
<td>[11.00,15.00]</td>
<td>12.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSI</td>
<td>0.55</td>
<td>0.473</td>
<td>0.503</td>
</tr>
<tr>
<td>FAR</td>
<td>2.928</td>
<td>2.473</td>
<td>1.223</td>
</tr>
<tr>
<td>DURÉE</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>To</td>
<td>[10.00,15.00]</td>
<td>[10.00,15.00]</td>
<td>[10.00,15.00]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSI</td>
<td>0.727</td>
<td>0.515</td>
<td>0.342</td>
</tr>
<tr>
<td>FAR</td>
<td>2.521</td>
<td>3.251</td>
<td>1.512</td>
</tr>
<tr>
<td>DURÉE</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>To</td>
<td>[10.00,14.00]</td>
<td>[10.00,15.00]</td>
<td>[11.00,15.00]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSI</td>
<td>0.827</td>
<td>0.741</td>
<td>0.816</td>
</tr>
<tr>
<td>FAR</td>
<td>3.732</td>
<td>2.9</td>
<td>1.49</td>
</tr>
<tr>
<td>DURÉE</td>
<td>5</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>To</td>
<td>[10.00,12.00]</td>
<td>[10.00,12.00]</td>
<td>[11.00,13.00]</td>
</tr>
</tbody>
</table>

Fig.9: Examples of generated solar envelopes.

The model makes it possible to maximize the FAR (Figure 9-a). Plot B has maximum FAR with a duration of five hours of solar access. Besides, the maximum FAR for plot C allows only one hour of solar access.

For maximum duration (figure 9-b), plot A doubles its duration but decreases its FAR of 43.33% compared to the first study. Besides, plot B has one additional hour of solar access impacting its FAR with a reduction of 23.93%. Plot C has 5 additional hours but its FAR decreases only of 24.36%.

By unifying the solar access duration to 5 hours of solar access (Figure 9-c), Plot A and C show a loss of 32.44% and 6.4% in FAR compared to the maximum FAR.
For 3 hours of solar access (figure 9-d), B and C show a loss of 10.79% and 7.85% in FAR compared to the maximum FAR.

The comparison of the results obtained with the current urban regulation of Tunis shows a clear improvement by using this model. We notice that this approach improves the maximum height indicated by the urban regulation. It can increase until 30m (Figure 10) compared to 17m as indicated by the actual urban regulation. The model allows building higher buildings guaranteeing solar access. This strategy optimizes the distribution of shade between neighbouring buildings in winter. This allows to increase the FAR for between 46% (for plot B) to 53% (for plot A).

![Fig.10: Height of buildings: (a) actual regulation and (b) for maximum FAR.](image)

We evaluate the solar energy for the generated solar envelopes. We calculate the solar energy received on them at the shadow cut-off time for winter and summer (Table 3).

**Table 3. Solar energy received on the solar envelope with maximum FAR in Winter and summer at the shadow cut-off time (kWh/m²).**

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Summer</th>
<th>Rdh / Rdw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plot A</td>
<td>98</td>
<td>187</td>
<td>0.524</td>
</tr>
<tr>
<td>Plot B</td>
<td>98</td>
<td>191</td>
<td>0.513</td>
</tr>
<tr>
<td>Plot C</td>
<td>101</td>
<td>185</td>
<td>0.545</td>
</tr>
<tr>
<td>A+B+C</td>
<td>99</td>
<td>186</td>
<td>0.532</td>
</tr>
</tbody>
</table>
We notice that Plot A and plot B have the same energy in winter (98 kWh/m²) but plot B has an excess of 2% in summer compared to plot A. Plot C has 3% more energy in winter than A and B. Besides, in summer it has the least exposure. It represents the best solution from an energy balance point of view.

5. CONCLUSION

We proposed a parametric model to generate solar envelopes for sustainable urban fabric. The generative design makes it possible to generate a digital model of the different density solutions by varying the solar access duration. Generative design can offer advantages to traditional urban planning processes, given its capability to manage complexity by optimizing heterogeneous preselected criteria. The virtual environment created allows exploring urban morphologies resilient both to urban densification and better use of the context resources.

This paper aims to optimize the solar envelope model by improving the shading cut-off time determination. We suggest defining it by a balance between the solar irradiation received in winter and that received in summer. The method proposed establishing the shading cut-off time to adjust the urban morphology to climatic conditions of solar access.

The goal of this approach is to exploit the morphological potential of each plot according to the climatic context of the project. The position, shape and size of the plot impact the FAR and the solar access time. The variation of the shading cut-off time allows manipulation of urban density while ensuring solar access over a useful solar access time slot. Plot A shows better results in density but the worst one for energy evaluation. Besides, plot C is the better solution for energy balance, but it is limiting urban density. This is due to the form and location of the plots.

The proposed approach makes it possible to guarantee better use of the solar resource on the building envelopes. Here, we have calculated the solar resource a posteriori. However, we can consider this variable as a parameter to select the optimal urban morphology. The study of the maximum FAR and received energy according to the shading cut-off time provides optimal solutions for each plot. The multi-objective approach would be necessary in that case.

We propose, in perspective, to refine the determination of the shading cut-off time according to the use and energy consumption. This being to adjust the morphology of the optimal solar envelope to the actual needs of the building. For example, assuming the installation of energy capture devices, if the shading cut-off time interval makes it possible to reach energy values that exceed the needs of a construction, the shading cut-off time could be reduced in favour of the neighbour.

REFERENCES