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Multiphysic Design of a Street Section

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Abstract. *The objective of the present work is to illustrate and discuss how numerical models can be used to simulate different physical phenomena that have a great impact on the comfort of buildings: acoustics and solar radiation, in order to:*

1) get estimations of the noise level, temperature and natural light on any facade as functions of the noise sources in the street and the local climate,

2) evaluate the sensitivity of these quantities with respect to some basic shape features,

3) and propose an approach to optimize the shape considering different requirements on the levels of noise (to minimize), temperature and/or natural light at the ground floor (to maximize).

1 Introduction

Ventilation, inertia, shading and insulation are ingredients of the four main strategies of bioclimatic architecture. It is also necessary to consider the characteristics of a particular climate, so as to compose these resources [Beckers 2012a]. Ventilation predominates in the hot and humid climates mainly found in the tropical regions. Where there is a large daily temperature variation, as in the tropical deserts, inertia is particularly welcome. Mediterranean architecture is mainly determined by the combined influences of light and shadow. Insulation is the key word in the cold regions.

With these principles, it is possible to design buildings where life is always better than outside, where maximum comfort is achievable at low energy cost. With the help of renewable energy, we can even consider “positive energy buildings”.

The urban scale introduces an additional difficulty, because the city itself is altering the climate locally. From the patterns of environmental physics, we begin to be able to quantify the evolution of the temperature of the urban air (Urban Heat Island) [Masson 2013]. From the patterns of building physics, we can manage the heat exchanges across the block or the district [Beckers 2012b]. Now, these two problems are linked. In addition to various physical couplings (solids, fluids, water cycle ...), multiscale aspects necessarily appear, which remain today a major challenge for modeling [Beckers 2016]. However, the inhabitants of the cities, their architects and their political representation do not see things in such a comprehensive way. For them, living in urban areas has essentially two consequences: less natural light and more noise. We might add: the quality of the views (privacy), the air quality (smelling, pollution), and the availability of transportation ... Most of these problems have a clear physical basis, but they are not coupled together by the physics: however, they are by the architecture and its usage. Thus, the sound waves and the heat do not interfere with each other, but excessive noise is forcing residents to close windows, even in summer, when cross ventilation would avoid air conditioning...

To address such issues, we have at our disposal tools to assist us for the efficient design, especially in the field of solar radiation [Beckers 2006]: we can design a solar protection, assess the photovoltaic potential on roofs, study light distribution in complex spaces. The contribution of optimization techniques then allows to dimension the openings [Fernández 2016] or to seek the optimal shape of a set of buildings [Vermeulen 2013] or a whole neighborhood [Vermeulen 2015].

However, to really accomplish the urban dimension, it is necessary to progress in three areas:

- Improving the quality and flexibility of the geometric model, built by procedural methods to wisely simplify the level of details of near [Besuievsky 2014] and far objects [Muñoz 2015];
- Define convenient parameters to quantify and qualify the light that reaches simplified interiors [Nahon 2015] or even just outside the windows, when the size of the geometric model makes no longer possible to model the interior [Nahon 2016];
- Improve and accelerate computational algorithms, using the best available projections [Beckers 2014b], in particular to distribute the incident energy on the sky vault [Beckers 2014c].

To include other areas in this process, starting with heat transfer in solids and urban acoustics, it must be agreed about the lowest common denominator to the models that we believe necessary. The natural candidate is the finite element method [Beckers 2016]. Today there are environments such as "Comsol Multi-physics" [Comsol 1998] where we can find all the necessary tools. The purpose of this paper is to present a first exploration of these environments applied to the simplest urban problem: find a street profile that gives the best compromise between sound, heat and light fields.

2 Physical Models

As a starting point, the first observation is that any street generates shadows. If it is oriented from north to south, as in the case studied here, the buildings have facades eastward, and they are sunny in the morning, or westward, and they directly capture sun rays in the evening. Sun radiation is composed of photons in short wave (their wavelength is ranging from UV to visible light and to near infrared, always below 4 microns). These photons can be absorbed by the surface they intercept. They then contribute to warming. If the surface is light in color, they are likely to be reflected, in general diffusely. In this case, the so called techniques of "radiosity" allow calculating at reasonable cost the full set of reflections [Beckers 2011].

Sound rays have very different behavior. In architectural and urban acoustics, reflection is mainly specular, and then it is necessary to capture this behavior in the design phase: the facades and balconies can be considered as a first approximation, as reflectors that guide sound reflection in the same way as mirrors do with light. The so called "geometric" methods (sound rays) then correspond to the right answer to the modeling task [Beckers 2009].

In general, the windows are the main places of exchange between the outside and inside (thermal and acoustic) and even the only one for light. The here studied configuration is shown in Figure 1. This is a street lined with two-story buildings equipped with balconies. It is proposed that these balconies have a form such that specular reflections from the street noise cannot reach the top floor (Figure 1 left). The upper windows will still have a good view of the sky factor (Figure 1 right), but the lower windows do not have anymore, because of the balcony. Seeing less of the sky, they also lose some of the direct solar radiation that would reach them either in the morning (east facing windows) or at night (west facing windows).

We imagine that the street is located in Quito, on the equator, and we are studying it on 21 September at the Autumn Solstice. That day, the sun rises exactly in the east, reaches the zenith at noon, and sets exactly in the west, after a journey of 12 hours (on the equator, every day is twelve hours long). So, the solar journey is exactly in the street section plane, and the thermal problem could, exceptionally, be fully solved in two dimensions.

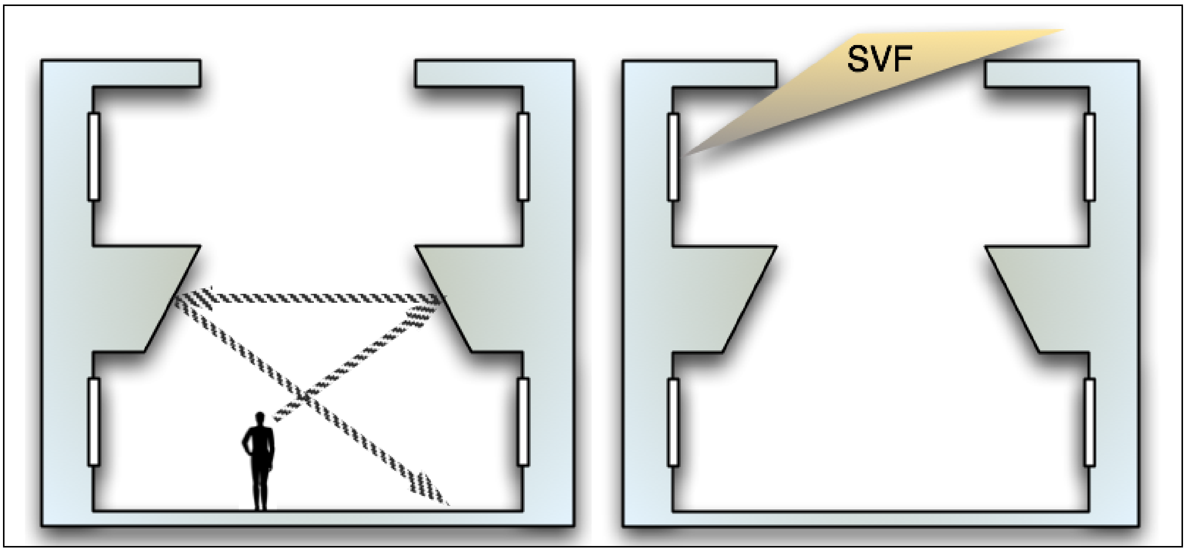

Figure 1: General configurations

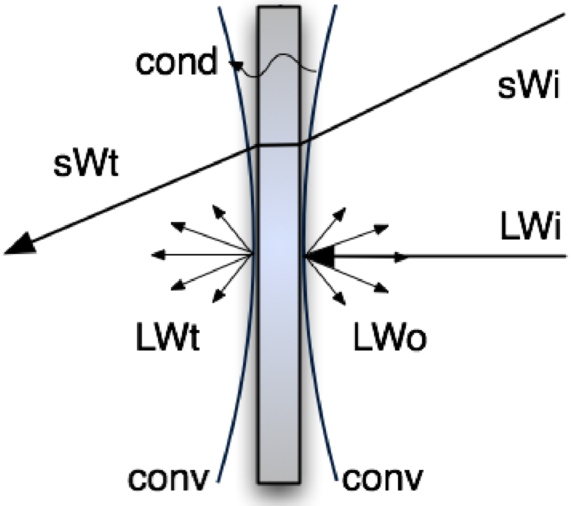

Figure 2 : Scheme for a window

Figure 2 shows the thermal balance on a surface. The incident shortwave radiation (sWi) reaches the surface, and partly crosses it (sWt) in the case of a window. Another part of the radiation is absorbed, as well as the incident long wave (LWi) radiation, which comes from the ground, the opposite façade and the sky. The absorbed heat passes through the wall by conduction and both surfaces of the wall in turn emit long-wave (LWo and LWt), according to the fourth power of their temperature (Stefan Boltzmann law). Finally, convection takes place on both sides of the wall.

3 Case Study

Figure 3 shows a symmetric 3D model of two buildings facing in a narrow street. The façade walls have a part overhanging in the street, which is parameterized with 2 design variables x1 and x2 (Figure 4).

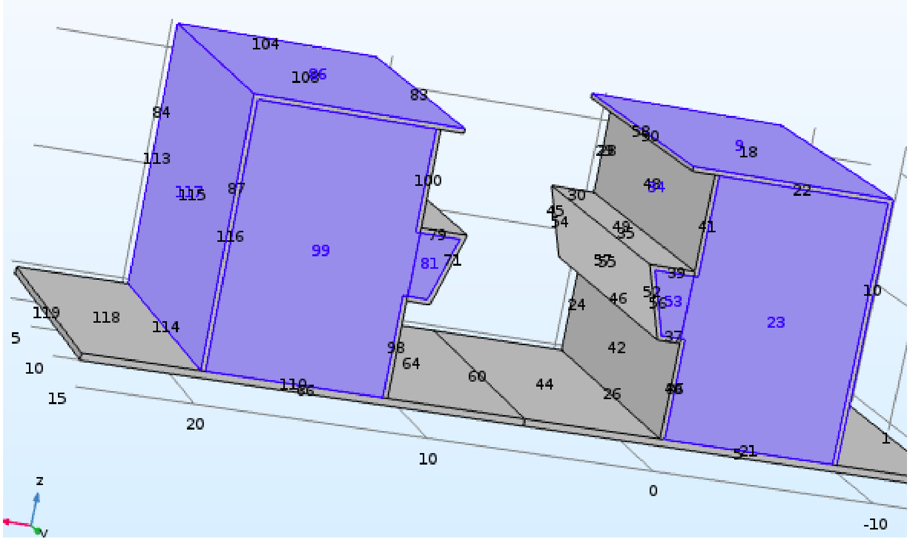

Figure 3: Model for 3D thermal analysis

Two physics are considered: acoustics and thermics. We choose to characterize the sound level by the sound intensity integrated on the first floor wall, and the thermal effect by the temperature of the wall at the ground floor.

The objective of the study is to evaluate the influence of the shape of the façades on these two criteria and to show how a final shape could be found in order to get the best compromise, depending on the two performance requirements that are imposed.

The acoustics model is defined by the surfaces which represent both façades and the ground between them; two “side” and one “top” virtual surfaces are necessary to close the domain.

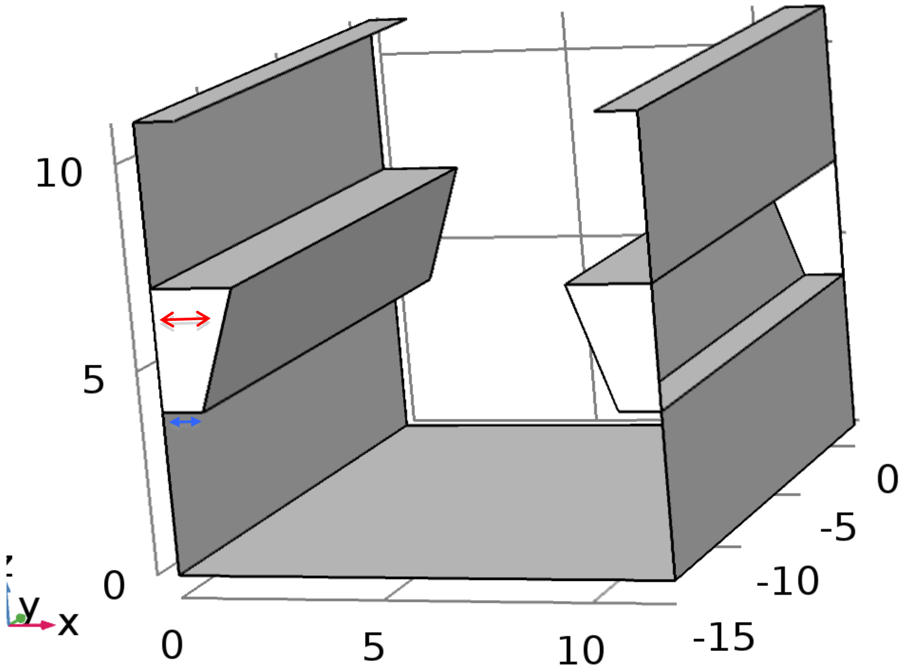

Figure 4 : Model for acoustic simulation

4 Optimization

4.1 Acoustical model

The acoustic model is defined by the surfaces which represent the two façades and the ground between them; two “side” and one “top” virtual surfaces are necessary to close the domain.

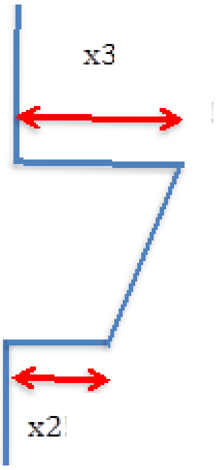

Figure 5 : Design variables

Shape	Intensity on upper floor wall, left side (W)
1: no balcony (x2, x3)=(0, 0)	$19.66\ 10^{-4}$
2 : balcony with inclined wall (x2, x3)= (0.5 m, 1m)	$3.12\ 10^{-4}$
3 : (x2, x3)= (1m, 2m)	$2.61\ 10^{-4}$
4 : balcony with vertical wall (x2, x3)= (2m, 2m)	$5.37\ 10^{-4}$

Table 1 - Sensitivity of noise level with respect to the shape

The sound source (0.001[W]) is located at the point S (x=4, y=-10, z=1.5) (Figure 4 and Figure 5); the walls are supposed to be made of concrete (specular reflection, absorption coefficient: 0.05); the sound intensity on the left wall, upper floor, is computed by using 40000 rays, which is the lowest number to get convergent values of the results; Table 1 presents the intensity corresponding to 4 balcony shapes.

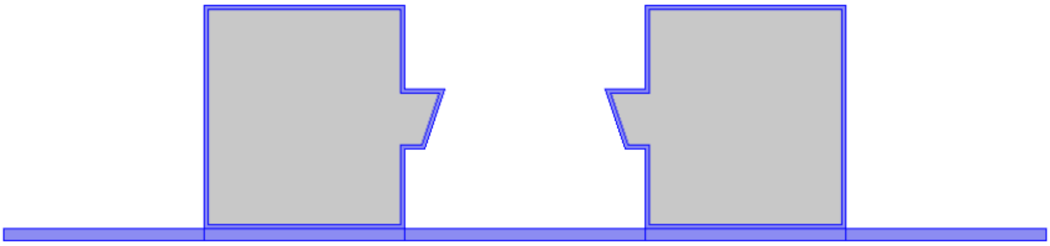

Figure 6 : Thermal study, 2D model

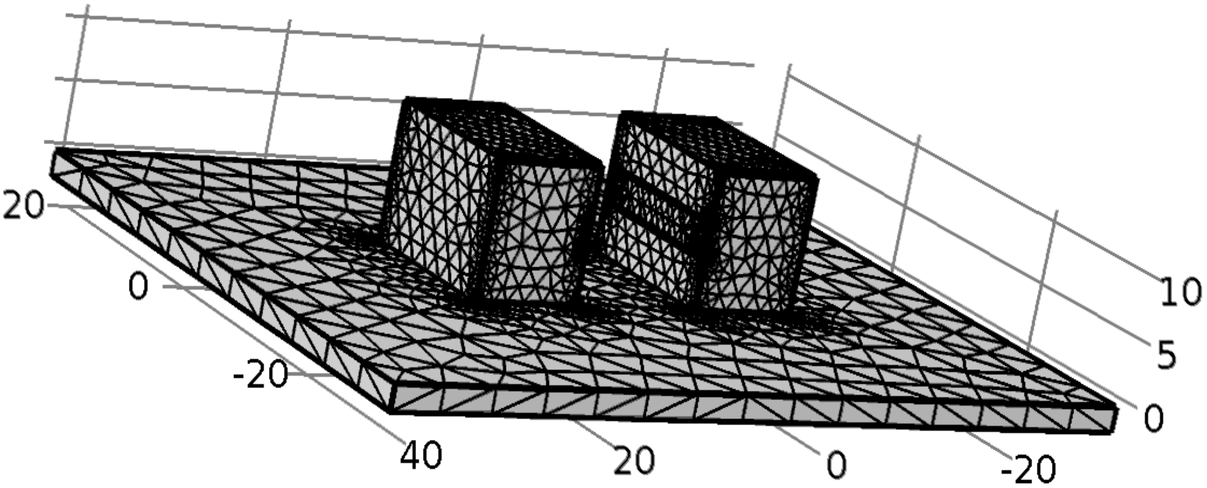

Figure 7 : Thermal study, 3D model

We observe that the presence of a balcony allows reducing the sound intensity by a factor up to 85 %; the lowest intensity is obtained for the shape 3.

4.2 Thermal Model

We consider now the thermal problem. The street is assumed to be located at (Lat: 0°, Long: 78°). In a first step, as we need only global quantities (average temperature on the surface of the walls), we simplify the problem by taking a 2D representation (Figure 6). In this case, the solar source is not considered; the variation of the temperature field with respect to the shape is very low, and it is not possible to determine the best solution because the precision of the model itself is not sufficient.

Therefore, we choose now a transient 3D model taking into account surface to surface radiation. It is necessary to mesh all the walls as 3D components, which gives a high number of degrees of freedom in the finite element system to solve (~50000 degrees of freedom, Figure 7), at each time step (every 30' from 5 a.m. to 7 p.m.).

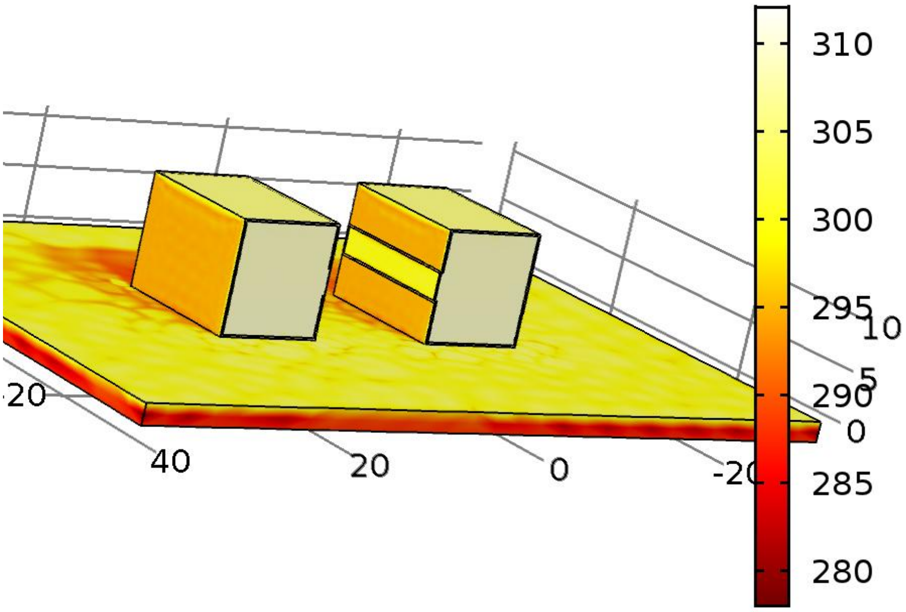

Figure 8 : Temperature field at 1 p.m.

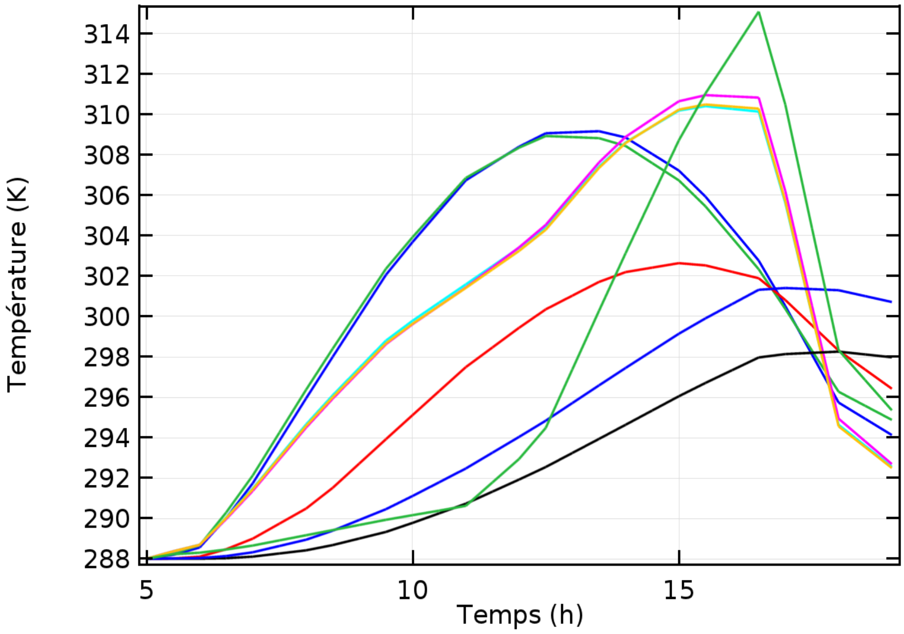

Figure 9 : Evolution of the temperature at different locations on the facades

As we can expect, this model provides more complete and more precise information (Figure 8 and Figure 9). The question is now: how to choose the type of responses to calculate: temperature, energy… and the time or location to consider: maximum/average/point values … to get "performance criteria" which are significant for architects or engineers? Even if some quantities seem almost equivalent, the optimal solution can be different for these criteria. In our example, if we are looking for the shape providing the highest average temperature on the wall of the ground floor, we find that the shape without balcony is clearly the best one. On the contrary, the average value on all external walls is almost insensitive to the shape.

4.3 Multicriteria solution

If we come back to our initial aim: to consider both acoustics and thermics, we see that the best solution for the thermal problem is in contradiction with the best solution for acoustics. It means that, in a general case, optimization has to find a compromise between the main physical phenomena that we consider as important. The easiest way to solve this kind of problem is to convert it into a constrained problem:

$$\begin{gathered} Minimize\ (or\ maximize)\ \ f(x) \\ with\!:\ g_j(x)\ \leq\ \ 0\ \ j=1,\dots,m \\ x=(x_1,x_2,\qquad \dots\ x_m\ )\!:shape\ variable \end{gathered}$$

$$\begin{gathered} f(x)\!:objective\ function \\ g_j(x)\!:constraint\ functions \end{gathered}$$

In the test example presented before, the objective function can be associated to acoustics (Min noise), and then the constraints could be defined by imposing a minimum level of temperature to satisfy at a given time $T(t_0)\ \geq\ T^{imp}$

There are very efficient numerical methods to solve this type of problem; moreover, some methods exist to estimate how the optimal solution varies depending on the limit value T^{imp}. Other approaches, which need a high number of numerical simulations, allow to find at the same time all the best trade-offs between the criteria.

5 Conclusions

Because optimization problems are dealing with iterative algorithms, a large number of simulations must be performed. So, fast numerical procedures are needed to solve the acoustic and thermal problems. They can be obtained by model reduction techniques or by response surface methods, which are both using a small number of high precision solutions to build explicit approximations, or by simplified models, for instance, models based on basic physics.

Today, new alternatives are also open. Indeed, the deep experience gained in the use of finite element method in the last fifty years for the solution of most engineering problems suggests revisiting old techniques to solve this application.

We have shown [Beckers 2015] that the heat flow element models, dual to the temperature ones, have an excellent behavior and allow performing error analysis. These elements are built with a set of degrees of freedom located on the sides in 2D or on the faces in 3D. For this reason, and because the simulations are dealing with radiative loads often related to radiosity methods [Beckers 2013], these models could give some improvement in the interpretation and the processing of the results.

With the same focus of improving the performance of the solvers, the superelement technique [Beckers 2113, 2014a] is expected to help in the handling of massive transient thermal problems including non linear boundary conditions.

References

[Beckers 2006] Benoit Beckers & Luc Masset, Heliodon2, Software, references & manuals (in French & Spanish), **2006**, http://www.heliodon.net

[Beckers 2009] Benoit Beckers & Nicoletta Borgia, *The Acoustic Model of the Greek Theatre*, Protection of Historical Buildings - PROHITECH 2009, June 21-24 **2009**, Roma, Italy.

[Beckers 2011] Benoit Beckers, Impact of Solar Energy on Cities Sustainability, in *Architecture & Sustainable Development, (vol.2, 395-400)*, Ed. M. Bodart & A. Evrard, Proc. 27th Int. Conf. on Passive and Low Energy Architecture (PLEA 2011), July, 13-15, **2011**, Louvain-la-Neuve, Belgium.

[Beckers 2012a] Benoit Beckers, “Worldwide aspects of solar radiation impact”, in Solar Energy at Urban Scale, chap. 5, Ed. B. Beckers, John Wiley and Sons, Inc., **2012**.

[Beckers 2012b] Pierre Beckers & Benoit Beckers, Radiative Simulation Methods, in *Solar Energy at Urban Scale*: 205-236, ed. B. Beckers, John Wiley and Sons, Inc., **2012**.

[Beckers 2013] Benoit Beckers, "Taking advantage of low radiative coupling in 3D urban models." *Proceedings of the Eurographics Workshop on Urban Data Modelling and Visualisation*. Eurographics Association, **2013**.

[Beckers 2014a] Benoit Beckers and Pierre Beckers, Super Element Technique for Solar Energy Optimization at Urban Level, *OPT-i, International Conference on Engineering and Applied Sciences Optimization*, 4-6 June **2014**, Kos Island, Greece.

[Beckers 2014b] Benoit Beckers, Pierre Beckers, Reconciliation of Geometry and Perception in Radiation Physics, John Wiley and Sons, Inc., 192 pages, July **2014**.

[Beckers 2014c] Benoit Beckers, Pierre Beckers, Sky vault partition for computing daylight availability and shortwave energy budget on an urban scale, *Lighting Research and Technology,* vol. 46 n°. 6, Pages 716-728, December, **2014**.

[Beckers 2015] Pierre Beckers, Benoit Beckers, A 66 line heat transfer finite element code to highlight the dual approach, Computers & Mathematics with Applications, Volume 70 Issue 10, November 2015, Pages 2401-2413.

[Beckers 2016] Benoit Beckers, Multiscale Analysis as a Central Component of Urban Physics Modeling, in Computational Methods for Solids and Fluids, Multiscale Analysis, Probability Aspects and Model Reduction, Adnan Ibrahimbegovic (Ed.), Springer International Publishing, 2016, Pages 1- 27.

[Besuievsky 2014] Gonzalo Besuievsky, Santiago Barroso, Benoit Beckers, Gustavo Patow, A Configurable LoD for Procedural Urban Models intended for Daylight Simulation, *Eurographics Workshop on Urban Data Modelling and Visualization*, April 7-11, **2014**, Strasbourg, France.

[Comsol 1998] Introduction to COMSOL Multiphysics®, Version: COMSOL 5.1, **1998**

[Fernández 2016] Eduardo Fernández, Benoit Beckers, Gonzalo Besuievsky, A fast daylighting method to optimize opening configurations in building design, *Energy and Buildings, Volume 125, 1,* August **2016**, Pages 205–218.

[Masson 2013] Masson V., Y. Lion, A. Peter, G. Pigeon, J. Buyck, E. Brun, "*Grand Paris" : Regional landscape change to adapt city to climate warming, Climatic Change* (**2013**) 117:769–782

[Muñoz 2015] David Muñoz, Benoit Beckers, Gonzalo Besuievsky and Gustavo Patow, Far-LoD: Level of Detail for Massive Sky View Factor Calculations in Large Cities, *3rd Eurographics Workshop on Urban Data Modelling and Visualization*, November 23, **2015**, Delft, the Netherland.

[Nahon 2015] Raphaël Nahon, Gonzalo Besuievsky, Eduardo Fernández, Benoit Beckers, Olivier Blanpain, Exploring metrics on the evaluation of the bioclimatic potential at early stages of urban project, *International conference CISBAT on "Future buildings and districts sustainability from nano to urban scale*", September 9-11, **2015**, EPFL - Lausanne, Switzerland.

[Nahon 2016] Raphaël Nahon, Benoit Beckers, Olivier Blanpain, Modélisation de l'éclairage naturel dans les premières étapes d'un projet d'aménagement, *34èmes Rencontres de l'AUGC*, Université de Liège, Belgique, May 25-27 **2016**.

[Vermeulen 2013] Thibaut Vermeulen, Jérôme Henri Kämpf, Benoit Beckers, Urban Form Optimization for the Energy Performance of Buildings Using Citysim, *International conference CISBAT on "Clean Technology for Smart Cities and Buildings"*, September 4-6, **2013**, EPFL - Lausanne, Switzerland.

[Vermeulen 2015] Thibaut Vermeulen, Catherine Knopf-Lenoir, Pierre Villon, Benoit Beckers, Urban layout optimization framework to maximize direct solar irradiation. *Comput. Environ. Urban Syst*. **2015**, 51, 1–12.