EC-CO-GEN: AN EVOLUTIONARY SIMULATION ASSISTED DESIGN TOOL FOR ENERGY RATING OF BUILDINGS IN EARLY DESIGN STAGE TO OPTIMIZE THE BUILDING FORM

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ABSTRACT

In the framework of the present study the software EcCoGen was developed from scratch, in order to assist the architects and engineers during the early design stages. More precisely, the environmental qualities of dynamic composite envelopes have been selected to guide the design through an evolutionary process. The main objective of the research presented here aims to attract more interest in the initial phases of the design, seeking to specify a tool that facilitates and encourages the creativity in the framework of bioclimatic design. Having under consideration the established and structured knowledge about the design process, the thermal properties of composite dynamic envelopes and evolutionary methods, we propose a tool based on an Interactive Genetic Algorithm (IGA) that is implemented in the original modeller software. Regarding the energy consum-ption evaluation in the initial design phase the method that we used is developed based on common energy model simplifications, and original developed regression models; however, at this stage the evaluation is limited to simplified seasonal heat loss model. In addition, it takes into account the solar gains depending on the orientation and inclination of the dynamic envelope's surfaces. Since this research focus on early design stages, the detailed description of the envelope is not possible. For this reason, the description of the inertia characteristics of the building remains approximate. Finally an original Graphical User Interface (GUI) is conceived.

INTRODUCTION

The concept of simplified energy analysis remains always a valuable contemporary tool even in the age of hi-tech computers. Detailed computer-aided building energy simulation software are effective tools that can be used as an aid to, not a replacement for, building designers in the decision-making process for morphogenesis optimization at the early conceptual stages.

In this framework, the research project presented in this paper has a dual focus. Firstly, the main objective is to enforce the applied research in architecture developing from scratch original software with the aim to integrate the sustainable development issues in the early design stages of buildings. Secondly, this research explores in which degree the use of EcCoGen can guide the designer to the emergence of new forms through a design process where the software may evaluate and question in an interactive mode (calculation time less than 1 sec) the environmental impact of the projectual strategies of the user.

Digital representations of architecture have been for several years a significant creative element of design research. Hence, our research project aims to define and develop a generative assisted design tool, whose operation is based on evolutionary mechanisms likely to bring a real help supporting the architect's decisions in early design stage. The instrumentation of such a creative design process is put in the context of sustainable development and energy savings. It is nowadays a priority in the fields of architecture and engineering to integrate the parameters and constraints of sustainable development through contemporary design approaches in order to guide the creation through innovative achievements.

GENERAL CONTEXT

Many software have been mainly used for CFD and detailed system modelling to assess the complex phenomena of building physics. In fact IES, EnergyPlus etc are the mainstream thermal design tools; however CFD and complex HVAC simulation are used much more rarely on complex project, while CFD is never used to calculate 'thermal performance'; it calculates airflow based on thermal boundary conditions usually provided from thermal simulation, in steady state normally. Other software such as MIT's Design advisor have been used as design support tools. Nevertheless, the estimation of building consumption in the later phase of design restricts the applicability and the innovative creation, mainly due to the lack of integration with geometry software applications and real time optimization.

This paper explores the newly developed original software Ec-Co-Gen that was created to integrate in early design stage most of the expert knowledge needed to optimize the building form in order to reduce its energy consumption. Based on an evolutionary process, the architect interacts with a population of optimized solutions. During the whole process, he still has the possibility to orient the evolution in a specific direction in function of aesthetic or subjective choices. An original Graphical User Interface (GUI) is conceived, where complex simulation model is embedded in it, however the interaction between the user and the software is permanently preserved.

Furthermore, this software is addressed to non-expert on thermal design issues architects; hence, no expert knowledge is needed to interact with the software. The main advantage of the software is that it suits in early design stage of the design process and not in the detailed one. In such a way, the user can interactively design building forms being more aware of the energy performance features and their impact on the energy consumption of the final building; however user's creativity is preserved because the GUI allows him to focus on the design without worrying about the model source code.

The output of the evaluation is a real time classification and evaluation of potential solutions through a real time comparison of the whole building's energy rating, its shading impact in the urban fabric and finally its compact shape. Starting with evolutionary tools precedents, this paper presents the main points of this design support, and especially of the Graphical User Interface, the thermal simulation mechanisms and the IGA's that drive the energetic simulation.

DEVELOPMENT OF EC-CO-GEN

The software framework

EcCoGen framework is based on two software Environement. The first one is Processing, an open source programming language based on java (*http://www.processing.org*). The Morphogenetic Engine, the Interactive Genetic Algorithm and all the Graphical User Interface are implemented with the help of Processing (Figure 1). The second sofware Environement is Rhinoceros® with its Grasshopper plug-in. Rhinoceros is a 3D modeler and Grasshopper allows an easy 3D programming. This environnement is used for the implementation of the evaluation engine based on the modified Unified Degree Day method extended and described below. The communication between the two environments is done using User Datagram Protocol (UDP).

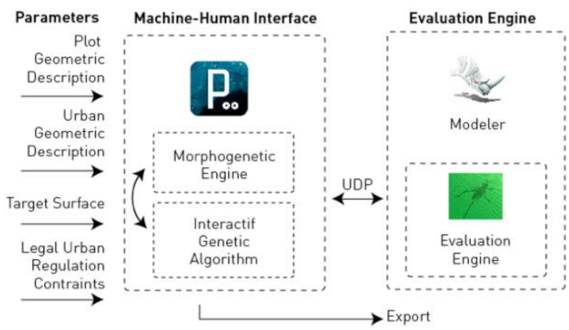

Figure 1: Software framework

A modified Unified Degree Day (UDD) Model

A Unified Degree Day (UDD) model has been modified to better predict the energy consumption of buildings during the initial design stages. The main purpose consisted to sufficiently reduce computerized techniques, which make hourly, daily and monthly calculation in order to be able to provide real time classification of the potential solutions. This method was chosen because of the simplifications it offers. Indeed, at the initial design stages, all the parameters are not clearly identified and it is necessary to make simplifying approximations. In this paper, we focus more specifically on the concept of winter comfort. This method (Cardonnel 2004; Martinaitis et al., 2010) dates fifty years and provides the determination of the sum of the temperature differences between a positive ambient temperature of 18°C and the outdoor climate over time.

Furthermore, in order to refine the calculation we enriched the standard UDD model developing and implementing new polynomial functions to forecast hypothetical composite dynamic envelope's thermal performance. Original software developed in the past that combines classic and novel modelling techniques has been used in order to have a precise and validated numerical investigation that focuses in a variety of possible composite dynamic wall's configurations (Mavromatidis et al., 2010; 2011; 2012a; 2012b; 2012c; 2012d). The model that is used to derive the polynomial functions takes into account the coupling between the solid conduction of both solid and fibrous systems and the gaseous conduction and radiation. The infrared radiation heat transfer through each layer has been modelled via the two flux approximation in order to take into account both optically thick and optically thin materials, as well as potential reflective surfaces currently used on composite wall's applications (Mavromatidis et al., 2010 ; 2011; 2012a; 2012b; 2012c; 2012d).

Different simulation scenarios have been conceived according to basic fractional factorial simulation plans in order to obtain valid empirical polynomial functions. To validate this statistical forecast system, many simulation scenarios were carried out and the statistical results are in compliance with the numerical simulations. The regression models' confrontation to the detailed numerical simulation data showed that the error caused by simplification is acceptable in most conditions, and a lot of coupling calculation could be saved (Mavromatidis et al., 2013). As a conclusion, the reduction of the complex numerical model to simple regression models in the form of polynomial equations and their implementation on the UDD model aims to improve the forecast capacity of the UDD model.

Finally, we also implemented on the UDD model the correlations and regression models that have been recently developed by Catalina et al (2008; 2011; 2013). These models had been constructed based on dynamic simulations of three climates (hot and humid, temperate and cold) for different shape factors in order to forecast heating specific consumption as a function of a set of independent variables (windows to floor area ratio, climate coefficient, south equivalent surface, building average U-value, building time constant).

Main modifications of the UDD Model

The general calculation formula of the UDD model is as follows:

$$D = H_t \cdot D_h(\theta\alpha) \quad \textbf{(1)}$$

where D are the building heating losses in *kWh / year* for the considered period, H_t is the loss coefficient of the building (both envelope's and ventilation heat losses) in *W / K*, $D_h(\theta\alpha)$ is the reference value of degree hours for the considered period in *K °Ch,* where D_h is a form of UDD integrated in hourly and non daily time scale, which allows to avoid the multiplication by 24; $\theta\alpha$ is the setpoint temperature in *°C*, optionally corrected in relation to the programming needs and the thermal inertia of the building. However, the losses (D) are partially offset by the free contributions of internal heating (AI) and direct solar radiation (AS). This heat recovery depends primarily on the relative contributions of free losses and the thermal inertia of the building. The earnings report on the loss during the heating period (γ) is calculated as follows:

$$\gamma = AG / D \quad \textbf{(2)}$$

To modify the classic UDD model, we considered the work of Catalina, Virgone and Blanco (2008) by employing the validated regression models that resulted from their study. That means that in order to assume the highest possible precision in our forecasting system, the *D-value in kWh / year* that represents the annual energy consumption is calculated according to Catalina et al (2008) using the following equation:

$$\begin{aligned} D &= 68.45 + 89.38x_1^2 + 5.27x_2^2 - 164.99x_3^2 + 2.3\cdot 10^{-4}x_4^2 + \\ &+0.017x_5^2 - 151.60x_1 + 201.63x_2 - 146.40x_3 - 0.051x_4 + \\ &+5.96x_5 - 147.26x_1x_2 - 26.27x_2x_3 - 0.102x_3x_4 + \\ &+0.002.5x_4x_5 + 48.31x_1x_3 - 0.0041x_2x_4 + 9.53x_3x_5 - \\ &-0.0041x_1x_4 + 4.63x_2x_5 - 2.96x_1x_5 \end{aligned} \quad \textbf{(3)}$$

where x_1 is the shape factor, x_2 is the average U value, x_3 is the building time constant, x_4 is the window to floor area ratio and x_5 the climate factor that is calculated from the monthly mean outdoor dry-bulb temperature and monthly average global radiation. The above regression model according to Catalina et al (2008; 2011; 2013) presents a mean coefficient of determination R^2*=0.9977* and Standard Error of the Estimate *SSE=2.615.* In order to model in detail the infrared radiation heat transfer and obtain a valid model for both optically thick and optically thin materials we developed 3 different regression models for 3 different composite dynamic envelopes' U values. Therefore, we used the 3 following equations (Mavromatidis et al, 2013):

For 1 layer envelopes:

$$\begin{aligned} 1/U &= 0.5708307 + 0.0092552y - 0.0009931\varphi - 1.3967974k - \\ &-0.0000071y^2 + 0.0000383\varphi^2 + 1.21817k^2 + \\ &+0.0000039(y\cdot\varphi) - 0.0094171(y\cdot k) - 0.0006031(\varphi\cdot k) \end{aligned} \quad \textbf{(4)}$$

For 3 layer envelopes:

$$\begin{aligned} 1/U &= 1.1694744 - 0.0001807x_1 + 0.0028826x_2 + \\ &+0.2121805k_1 - 0.5928034k_2 - 0.0004819\varphi \end{aligned} \quad \textbf{(5)}$$

For 5 layer envelopes:

$$\begin{aligned} 1/U &= 1.7054769 + 0.002142602475\cdot\varphi + \\ &+0.0051330617625\cdot y_1 + 0.0062850496625\cdot y_2 - \\ &-0.004380920775\cdot y_3 + 0.010406153625\cdot y_4 - \\ &-0.01267569695\cdot y_5 + 0.010316348175\cdot y_6 - \\ &-0.3643861134875\cdot k_1 + 0.75388161375\cdot k_2 - \\ &-1.1719444560375\cdot k_3 + 0.622647211925\cdot k_4 - \\ &-0.105649743575\cdot k_5 + 0.3112130777125\cdot k_6 \end{aligned} \quad \textbf{(6)}$$

where φ is the inclination angle in °, y is the thickness of each layer in *mm* and k is the thermal conductivity of each layer in *W/mK*.

Before their implementation in the Ec-Co-Gen software, the above regression models have been validated and evaluated on the basis of a point to point confrontation to detailed numerical simulation data (for details see also Mavromatidis et al, 2013). More precisely, for the equation (4) we obtained a very high R^2 value equal to *0.9628*, while both *bias score= -0.00160473* and *RMSE = 0.06428987* are in satisfactory levels. For the equation (5) we obtained a very high R^2 value equal to *0.9884*, while both bias score and RMSE are in satisfactory levels where in this case study *bias score= 0.006822585* and *RMSE = 0.047847828*. Similarly, for the equation (6) R^2*=0.99123,* while *RMSE = 0.0284532 and bias score= 0.007923585.*

As a conclusion, the above-mentioned modifications have been implemented to a classic UDD model (further details on the UDD model used for the development of EcCoGen can be found in Marin, 2010).

Solar gain evaluation

Regarding the calculation of solar radiation on a wall whose position is characterized by its inclination to the horizontal plane (s = 0° for an horizontal wall, s = 90° for a vertical wall, etc), and the solar azimuth (γ = 0° for a wall facing south, γ = -90° for an east wall, γ = 90° for a west wall, γ = 180° for a north wall), we are calculating the angle of incidence as follows (we call *cosV*, *cosW* and *cosS* the direction cosines of sunlight), while these cosine formulas are deduced:

$$\cos V = \sinh = \sin\varphi + \sin\delta + \cos\varphi \cdot \cos\delta \cdot \cos H$$
$$\cos W = \sin Az \cdot \cosh = \cos\delta \cdot \sin H \quad \textbf{(7)}$$
$$\cos S = \cos\delta \cdot \sin\varphi(\cos H - tg\delta/tg\varphi)$$

where h is the elevation of the sun expressed in terms of inclination to the horizontal plane angle, Az is the sun's azimuth in relation to the South, φ is the latitude of the observation point and δ is the sun's inclination (steering angle of the sun in comparison to the equator plan). The direction cosines of the normal to the wall are : l=cos s, m=sin γ sin s, n=cos γ sin s. The solar beam's angle of incidence on the wall is then provided by the dot product of the normalized vectors (cosV, cosW, cosS) and (l,m,n) as follows:

$$\cos i = l\cos V + m\cos W + n\cos S \quad \textbf{(8)}$$

Therewith, we assume the direct flow (I) to be perpendicular to the sun's rays as follows:

$$I = I_0 \cdot C \cdot A \cdot \exp\left(-B/\sinh\right) = I_0 \cdot C \cdot \theta_D \quad \textbf{(9)}$$

where I_0 is the solar constant equal to 1380 W/m², C is the coefficient of Earth-Sun distance, h is the height of the sun above the horizon, A and B are the disorder coefficients, whose values are respectively recommended, for a clear sky, under normal conditions, or in an industrial area, A is equal to 0,87, 0,88 et 0,91 and B is equal to 0,17, 0,26 et 0,43 for each case and θ_D is the transmittance of the direct flux. In case of an inclined wall (where i is the inclination angle) the direct flow on the wall is calculated as follows:

$$P_D = I \cdot \cos i \quad \textbf{(10)}$$

Finally, the diffuse flux (Φ_d) on a horizontal surface is given from the following formula:

$$\Phi_d = I_0 \cdot C \cdot \sinh\left[0.271 - 0.2939 \cdot A \cdot \exp\left(-B/\sinh\right)\right] \quad \textbf{(11)}$$

while the diffuse radiation on an inclined wall is calculated as follows:

$$P_d = \left(1+\cos s/2\right)\Phi_d + a\left(1-\cos s/2\right)\left(I \cdot \sin h + \Phi_d\right) \quad \textbf{(12)}$$

where a is the soil's albedo coefficient. This method allowed us to determine the instantaneous values and cumulative solar radiation on a wall at any point on the earth at any moment. However, in our evolutionary prototype evaluation the radiation is not been calculated using this method, but will be based on linear interpolation of precompiled irradiation values at established angles. Nevertheless, the pre-compilation is done using the abovementioned method.

Main points of the original Interactive Genetic Algorithm (IGA)

Our interactive genetic algorithm (IGA, figure 2) aims to introduce creativity within the generative strategy, bringing accurate optimization, exploration and inspiration capabilities for architects and engineers. For this reason, it is an evolutionary strategy derived from Jaszkiewicz MOGLS (Jaszkiewicz, 2002) and continuously improved with recent advances on adaptative parameters tuning ACROMUSE (Mc Ginley, 2011) in order to preserve high performance while maintaining high diversity.

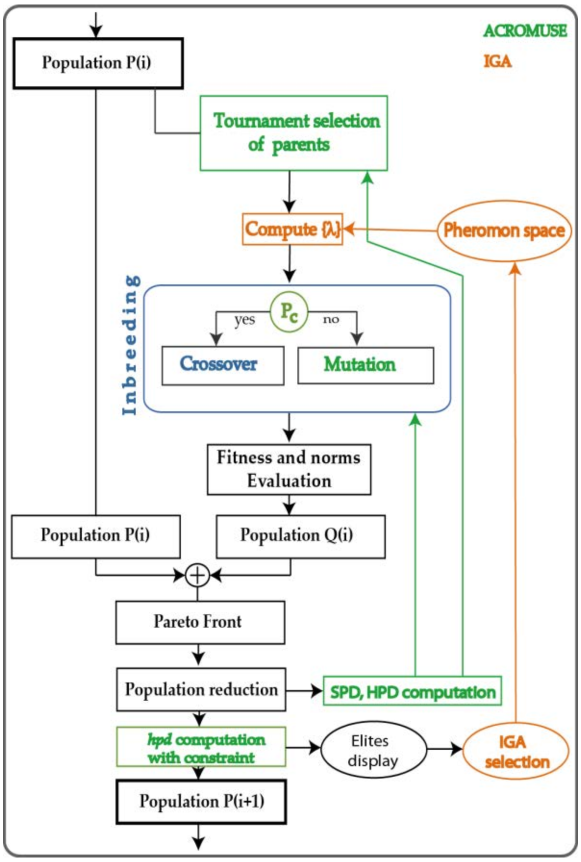

Figure 2: Main points of the IGA framework during 1 iteration step.

During the process, the architect interacts with populations of optimized solutions and still has the possibility to orient the evolution in various specific directions, according to performance or subjective choices (marginal optimization). Our algorithm mixes genetic capabilities with pheromonal approach derived from Ant Colony Optimization (Angus et al., 2009), in order to enhance the user's creativity with persistance and evaporation features. The underlying concept is to achieve improved performance via evolution while keeping certain resemblance with the user selected choices. Thus, our IGA behaves as an implicit user preferences learner with coherent and stabilization effect.

Conception of a GUI

The Graphical User Interface is organised by two screens. The main one allows the elite population visualisation, the second one zooms in the phenotype representation. The first screen is divided in three main parts (Figure 3): the current elites population, the selected individuals collection and the algorithm preferences composed by the evaluation parameters and the constraints values.

Figure 3: Main screen with elite population visualisation.

The architect has the possibility to select one or more individuals and to keep them available for subsequent manipulations. These selected individuals constitute a collection. At any time during the process, the architect can export them or inject them inside the evolutionary loop in order to redirect the optimization, to rebalance the Pareto front by favouring these new entering.

Figure 4: Zoom window, 3D interaction and performance outline visualisation.

The zoom window (Figure 4) presents the phenotype representation integrated inside the urban context; it is possible to manipulate the 3D model in rotation and to display the performance outline. These two kinds of information allow both a subjective interpretation and an access to an objective knowledge, the relative and the absolute performance of the building.

RESULTS AND DISCUSSION

EcCoGen belongs to the family of tools based on a generative genetic algorithm. The software generates solutions evaluated according to certain criteria, including energy performance. The solutions considered effective are crossed to generate other solutions. EcCoGen tries to achieve two objectives: browse a large solution space ensuring greater diversity of offered items (diverge), and at the same time increase the efficiency of families of solutions that seem the most appropriate to each case study (converge). EcCoGen does not find THE most effective solution. It allows the user to browse a space of very wide range of different solutions, and select solutions potentially performing according to his subjectivity. Each launch of EcCoGen for the same initial data, site and constructive program, can guide to other families of solutions that can be equally effective.

EcCoGen has been simultaneously developed in two phases. The first phase consisted to design and develop a simple enough energy evaluation engine, which can be easily adapted to almost all configurations of any composite envelope. For this purpose, we developed -employing an original sophisticated numerical model- regression models to forecast hypothetical composite dynamic envelope's thermal performance, since the objective is to create an interactive tool (calculation time <1 sec). The second phase involves the consideration of environmental parameters in short, medium and long term in the evaluation mechanisms for the energy performance of a whole building. As a first approach we employed the Unified Degree Day Method (UDD) that is a single-measure steady-state method suitable for heating energy consumption estimates of small buildings. Although energy estimates from UDD calculations are approximate, they helped us to obtain an idea about the energy consumption trends for small buildings. Hence, we choose UDD method only as a first approach, because of the fact that our initial objective during this first phase of the project was to characterize the severity of a climate being very useful in energy estimate calculations for comparing the heating requirements from one location to another in the framework of morphogenesis. In order to refine the calculation we enriched the standard UDD model employing the polynomial regression models that we developed and evaluated in the framework of this project as well as other validated polynomial models found in the literature on scale, regarding the energy consumption estimation of buildings.

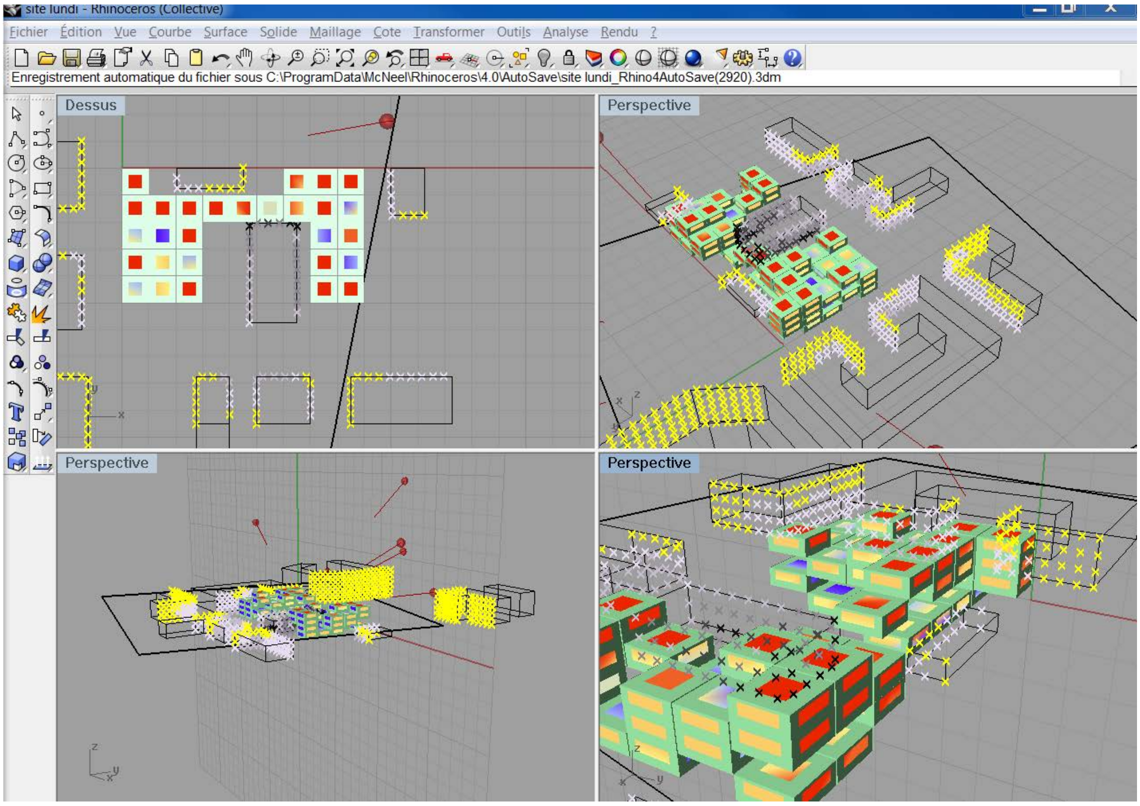

Figure 5: Real time fitness evaluation in the Rhinoceros software.

EcCoGen can also operate with minimum human intervention, trying to improve the families of solutions already found, through the emergence of other families. However, it also works in interactive mode: the user can select at any time, among a variety of different solutions displayed on the screen, the solutions that seem interesting for him.

The criteria chosen by the user could be aesthetic, functional and constructive, as they can be based on an analysis of the potential solution's performance calculated and presented by EcCoGen. For example, the user can choose to focus on the compactness of the form rather than on another energy criterion. EcCoGen preserves certain characteristics of the selected objects, while it continuous optimizing and evaluating in real time their overall performance.

In its present version, where only some criteria are evaluated, EcCoGen was tested in laboratory configuration (Figure 5). The main aim was to initially observe the potential changes in projectual strategies that the tool induced during an exploratory approach in limited time, during a design exercise reproducing operational practices (case study : concrete architectural conception from urban data and in the framework of a specific program). The above-mentioned experiments gave some first conclusions:

- The tool allows emerging morphologically unconventional solutions;
- It educates unconsciously the operator-designer on environmental performance issues which he generally pays attention a posteriori ;
- It asks the designer on the prioritization of the preferred performance issues (heat, light, functional, constructive);
- Expected results are highly correlated with the local characteristics of the case study (orientation, exposure, exposed surface ratio / protected area, altitude, adjacency);

- It preserves a high degree of interaction between the designer and the tool, including the necessary preliminary knowledge both in the field of eco-performance and in understanding the mechanisms of emergence, selection and optimization solutions;
- It makes the designer to focus on the role of creativity during the process of eco-conception inside the framework of sustainable development;
- Finally, the tool enriches the user's ability to overcome classic formal eco-friendly morphological vocabularies, and create original and innovative morphologies, more suitable for local contexts (considering micro-climate and sustainable development issues /Figure 6) .

Figure 6: Morphogenesis in the framework of sustainable development by preserving non uniform optimized solutions.

CONCLUSION AND PERSPECTIVES

We would like to conclude by clarifying some aspects more generic, relating to the issue of generative modelling and resume our initial assumptions and aims. We believe that the implementation of a computerized support tool cannot carry in itself a holistic approach. The medium is necessarily limited in its representation, leads to certain types of comprehension and expression, but can allow completeness. The quality of the designer lies in his ability to convene in a relevant way the right tool at the right time. And for the same reason a generative device, cannot take into account all the project variables. Inevitably, it operates on a limited number of parameters, while the quality of designer is the function of the relevance of his/her choices. Generative tools do not provide an answer to the whole problem; they are only a piecewise expression for a part of the understanding. However, their operating procedures are characterized by an explicit expression process facilitating a subsequent visual interaction. For this reason we often return to that point that seems crucial.

Furthermore, an intensive study questioning if the architect's creativity is enhanced by EcCoGen has been carried out by our partner *Codysant-Interpsy* (French Lorraine University) and concluded that the first feedbacks of the users confirm the potential of the software to assist the decision-making processes of the designers, preserving at the same time their creativity. Furthermore, it has been observed that the IGA enriched the variety of the potential environmental friendly solutions. The most interesting thing is that there is no uniformity of the proposed solutions and these solutions depend on the subjectivity of the user who continuously interacts with the tool. For these reasons, the software presented here aims to be a gateway to a profound change in morphogenesis decision-making processes through architectural design adapted to emerging issues, such as energy consumption in the building sector and sustainable development.

Even if EcCoGen is an attractive assistance tool at the early design stages, in the future, our main preoccupation deals with the need to enrich the energy evaluation engine in order to be able to make an assessment under transient dynamic conditions. The UDD method was attractive enough because of the rapid calculation; nevertheless, it is only good for heating estimation. However, in the future, our main purpose is to be able to estimate also cooling energy loads. Furthermore, we remarked that employing the UDD method, there is no precise consideration of internal heat gains. Applicability is limited to residential buildings and similar skin-load dominated structures where envelope transmission and infiltration are the load dominating factors. We also remarked that the UDD method is conservative. With better insulation levels and increased internal loads, the building form's efficiency can be overestimated. Finally, the main disadvantage of the UDD method is that it is based on average conditions and does not account neither for day-to-day weather variations nor for the effect of temperature on equipment performance. For these purposes, in our future research we intend to substitute the UDD method by developing a variety of simplified type RC (resistive-capacitive) thermal models. Finally, the appropriate design of in situ experiments in scale of 1 to validate if the energy evaluation engine is robust enough is needed.

The whole proposal is clearly the first approach of an ambitious research project that we are always in train to enrich and has as main objective to enable the implementation of the results of previous research in environmental science and building physics, reducing the gap between architectural design and current scientific knowledge on sustainable development issues.

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