An interactive and generative eco-design tool for architects in the sketch phase

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Abstract. This paper presents the latest version of our software, EcoGen2.1, to the Building Simulation community: a quite advanced prototype for generative eco-design, resulting from a French ANR project, having been the subject of a deposit with legal protection, and recently used to assist the architectural design of an emblematic building in a competition in France. The tool is adapted to the sketch step of the design, when it comes, in a given urban and climatic context, to composing the general forms of a building or a plot of buildings, depending on various criteria that ensure a sufficient level of efficiency in view of bioclimatic and environmental requirements, notably relating to solar energy, thermal consumption and luminous comfort. We have focused on the technical work involved in breaking major difficulties when trying to develop real time and interactive software devoted to generative eco-design in the early stages of an architectural project.

1. Introduction
Designing an evolutionary decision-making tool in the sketching phase, accessible to architects, requires the development of computation codes that are robust enough to work from incomplete or inaccurate data and problems [5], but also sufficiently fast to greatly reduce the latency with which the user is confronted.

Our software concerns three key moments of the design process: morphogenesis, evaluation and optimization, helping searching for solutions (to a given architectural program) that show a good compromise of performances. Its algorithm is designed to generate and evaluate thousands of individual solutions in interactive time, and quickly converge towards the best, while presenting a variety of possibilities. Therefore, it is under study for an extension to the eco-design of urban islets.

1.1. A unique tool that is part of the designer's resources
Unlike most building engineering calculation tools or architectural CAD, which are more appropriate for describing, simulating and analysing the technical, energy or environmental performance of a detailed project than for helping architects formulate a sketch, ours is not a post-project control software. It has an ability to:
- generate one or more eco-efficient buildings within a built environment (islet, plot);
- evaluate in real time certain performances of the architectural forms produced during the sketching phase;
- stimulate the architect's creativity by proposing families of morphologies adapted to local contexts (urban and environmental);
- interact with the architect in search of effective, original and personalized solutions;
- facilitate dialogue between architects and design or control offices.
1.2. From generative design to interactive design
EcoGen belongs to the generative design family, whose form finding logic results from a parametric optimization process [7]. Technically, it is composed of four modules: an interface, a shape generator, a multi-criteria interactive genetic algorithm (IGA) and a performance evaluation engine, all developed in Java and C++ / OpenMP.

The IGA, based on [6][12] and equipped with a programmatic constraint solver, iteratively generates a number of solutions that are crossed and varied to create new families that perform better according to the chosen criteria. The evolution can be observed over a few tens to hundreds of iterations, depending on the size of the project.

The algorithm works either in stand-alone mode (pure optimization) or in interactive mode. Here, we have sought to overcome the limitations of a computational generative process, by combining it with the user’s cognitive processes, taking into account subjective or functional choices made within an evolutionary process. In this case, the user indicates to EcoGen the solutions of the Pareto front that seem interesting to him to be hybridized later with others (including those coming from different simulations). But, unlike BioMorpher [4], for example, it continues to maintain a certain diversity and optimize the rest of the population. Thus, it behaves like an intuitive design assistant: influenced by elements outside the optimization criteria field, source of proposals and analytical data in the creation phase.

1.3. From the operating context to morphogenesis
Urban planning rules are synthesized in an available capable surface (‘figure 1’ in blue), the extrusion of which forms a capable volume (in the sense of Rem Koolhaas). This volume is cut according to a 3D grid, each cell representing a topological and functional unit (e.g., housing, office, retail, ‘figure 1’) called voxel, whose dimensions can be adjusted according to the size of the building to be designed, or set on a standard 1.3 m module. They remain the same for a given session (choice related to the search for algorithmic and computational performance). The maximum height of the building and the floor area are set by the construction program. A tolerance can be defined by the user to explore less constrained shapes.

Morphogenesis works by activating and aggregating voxels respecting a functional distribution from the program. In order to encourage more ambitious formal research, EcoGen2.1 allows a quantified rotation (in 10° steps) of this volume (‘figure 3’), respecting a distance from the built environment, and a slope of the walls (in 5° steps). Architectural forms with overhang can thus emerge from optimizations of solar capture and interaction with the site, favouring solutions that are not necessarily aligned with the road axes.

2. Performance design and form emergence
Changes in regulations have encouraged the early integration of energy simulations into the design process [3]. As a result, our evaluation engine situates the solutions in their climatic and urban environment, then makes calculations inspired by an economical, passive and environmental architecture.

2.1. Light comfort inside the built spaces with opening windows
Our Daylight Factor performance optimizes the potential for natural indoor lighting in the regulatory comfort range [2%, 5%]. It also disadvantages the appearance of excessively deep levels in favour of so-called “through forms”, much appreciated by architects, particularly to improve natural ventilation. Starting from a validated polynomial regressive model [9], the Daylight Factor has since been adapted to morphogenesis based on multiple voxels (publication in progress). It takes into account the diffuse contributions of the celestial vault and provides an "equivalent glazed surface" for each wall.
2.2. **Compact form factor**

We use a dimensionless version of the compactness allowing the comparison of the generated volumes without the impact of the scale factor (sphericity). It aims to reduce the economic cost of the project (especially for passive buildings) and loss surfaces, to simplify its structure and internal circulation and to aggregate the voxelized volumes.

2.3. **Solar contributions and courtesy**

Unlike the research described in [10], the evaluation and optimization of the overall solar gains received by the built envelopes, conducted on the scale of the block and not the building, are in line with the need to pool energy. They are carried out by a calculation engine for solar gains and shading masks (partly pre-calculated on the envelope elements of the buildings of the site interacting with each other from the point of view of light). Developed in our laboratory (patent pending), it is scalable in spatial and temporal dimensions. The performances developed include direct, diffuse and reflected contributions from the ground, but also solar courtesy on the neighbourhood (right to the sun from October to April, right to the shade from May to September). Finally, the photovoltaic potential on the roof or facade is immediately evaluated on the basis of the previous results.

2.4. **Heating consumption**

Our algorithm evaluates the thermal performance in terms of heating consumption over the period “October to April” from the Catalina polynomial [2] based on numerous simulations for different European climates. We have adapted it to the needs of a realistic modeling of voxels, whose wall and glazing characteristics (surface, insulation, opening rate, orientation, inclination) are for the moment fixed and set on the French RT 2018 and BEPOS 2020 standards, particularly in the absence of economic criteria limiting excess.

![Figure 1](image)

**Figure 1.** A proposal of the software optimizing heating consumption (3 types of voxels).

2.5. **Summer thermal comfort**

In order to limit the summer overheating of rooms exposed to the sun, and without considering the inertia of the building, our solution consists in: reducing solar gains on the most exposed glazed façades, increasing the solar collection surface for the installation of photovoltaic devices for cooling and promoting the right to shade in neighbouring buildings. It is therefore a compromise between contradictory trends.
2.6. Interactivity and computation time
We have implemented evaluation mechanisms based on exact calculations (e.g. occlusion detection) or metamodelizations (from a large number of simulations performed prior to the construction of the models [1][10]). And thanks to the development of optimized and parallelized algorithms, it has been possible to achieve evaluation times in the order of a thousandth of a second (on a 8 cores CPU), encouraging the exploration of a large number of solutions in interactive time.

![Figure 2](image_url)

**Figure 2.** A software compromise between daylight factor and compactness (3 types of voxels).

3. Ergonomics and creativity
The main concern was to drive architects to accept a digital optimization tool that does not limit their creativity, but on the contrary enhances it by proposing to:

- explore solutions that are uncommon in terms of morphology, but effective in terms of energy and environmental efficiency (‘figure 1’, ‘figure 2’);
- present multidimensional results - theoretically complicated to read - but made accessible, via appropriate indicators, to non-experts who can rely on them with confidence (‘figure 3’);
- show the designer only the most interesting shapes, by judiciously sampling Pareto's front on a criterion mixing performance and diversity, also facilitating the understanding of the couplings between form and performance (often neglected in the sketch phase);
- visualize and examine in several ways the different solutions generated, annotate them, keep them or direct their optimization in directions resulting from favorite selections (‘figure 3’).

Feedback from architects, including during the competition phase, shows that the trust placed in the software's proposals contributes to a creative freedom that other assistance or post-control tools do not allow. EcoGen2.1 is used as an idea generator, a mediation support, whose bioclimatic performances remain the driving parameters.

4. Conclusion
In terms of appropriation, the software prediction of the multi-criteria behaviour of the project often meets the expertise or intuition of the designer. By taking into account at a very early stage the technical considerations that an architect finds it difficult to address, EcoGen2.1 can help to associate technicality with design, an essential objective for sustainable development. It simplifies the work with professionals in each specialty and the number of feedbacks required.

But in terms of acceptability, it arouses both the curiosity and reluctance of designers. Indeed, the priority object of the architect's work is not the form, in general, but the design process, the hierarchy...
of spaces, the circulation, the uses, the constructive solutions and the sensitive criteria, not treated by the software.

However, it is a new way of entering the project, where bioclimatic performances precede creative intuition. The tool arouses interest for its simplicity of use and the proposal of sometimes unusual shapes. The architect does not feel he is dictating how the software should be used: he still has to appropriate what is proposed and translate the arrangement of the voxels into a formal vocabulary closer to his aspirations.

Figure 3. Our software main interface : incubator view of the genetic process.

5. Future works
The constant search for eco-efficient architectural solutions that satisfy the user leads us to consider:
1) life cycle analysis and overall cost (a challenge in the sketch phase [11], where the introduction of a project cost over the life cycle of the building is mandatory to limit the costly technical solutions that emerge from optimizations); 2) parametric optimization of envelopes: for more precise calculations, one option is to replace in Catalina's metamodel the thermal resistance of a composite envelope element by polynomial metamodels [8]; 3) the exploration of morphogenesis modalities other than voxel, despite its algorithmic simplicity and the time saving in evaluation that it allows.

Finally, deep learning should make it possible to consider a radical overhaul of the way we approach assisted conception from an AI perspective. It places human thought and learning at the heart of the decision-making process, ergonomic and cognitive issues essential for their acceptability in operational situations.
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