Digital fabrication of a brise-soleil using fractal geometry as generative system

Maycon Sedrez¹, Rafael Meneghel², Gabriela Celani³
¹,²,³ Unicamp
¹,³ http://lapac.fec.unicamp.br/
¹,³ {maycon|celani}@fec.unicamp.br
² rafael.meneghel@gmail.com

Parametric design and digital fabrication are becoming ubiquitous tools to contemporary architecture and imply a different design process. With this new perception of the contemporary production we have designed a façade sun shade using fractal geometry as a generative system. Fractals are complex shapes generated with simple rules, so it is relatively easy to change the final geometry when we work with parameters. The design process made possible the creation of different options for the brise-soleil using parametric definitions. Some solutions were physically modeled using rapid prototyping, which we consider an essential tool in the contemporary design process. The whole process conducted to the conclusion that architects need to incorporate a new set of skills when working with digital fabrication. Keywords: fractal, design process, generative system, digital fabrication.

Keywords: fractal geometry, generative system, digital fabrication, design process

INTRODUCTION
Fractals are present in buildings of different historical periods, even before the publication of the seminal work of Mandelbrot (1983): The fractal geometry of nature. But the use of fractal geometry in architecture really started in the 80’s with Peter Eisenman (Ostwald 2009). For Ostwald (2001), the appropriation of fractals by architects appeared after the year of 1978 and continued through the 80s. In the 90s fractal architecture had its decline due in part to the exhaustive use of the expressions "complexity theory" and "chaos theory", and their many contradictions. Nevertheless, it is possible to see that some architects still use fractal geometry in their designs nowadays, as a generative system for creating forms. The return of architects’ interest in mathematics and geometry supported by digital technologies in the creative process and the production of complex forms has favored the presence of fractal geometry in architecture. The use of computer programming also contributes to this design process, allowing iteration and recursion functions, which are some of the main characteristics of fractals. In the search for complexity, architects are designing and producing forms with digital fabrication, which has resulted in what has been called "new ornament" (Picon 2010, Picon 2013). In this context, fractals are an important component to be explored in the creative process.
**Hypothesis and objective**

The objective of this research is to explore fractals parametrically in the design process, aiming a contemporary type of ornament, which is also the result of a search for environmental performance and the digital fabrication of complex forms. In the next sections we will explain what fractal geometry is and give examples of its uses in architectural design; this will lead to the discussion of complex forms in architecture, design and production. Finally, we will explain how digital design is enabling this new type of ornament. The product of this research is an ornamental façade designed with fractal geometry, which will be described in section Design Method. It is first necessary to present the concept of DAD (Digital Architectural Design), as explained by Oxman (2008): "new relations between digital form and digital processes are contributing today to the emergence of a new conceptual vocabulary". This author proposes three models of study: formation, generative and performance models. In the present work we have explored the generative model, in which "shapes and forms are the result of a generative process" (Oxman 2008). Examples of this model are evolutionary algorithms and shape grammars. We have surveyed some examples of how to explore fractal geometry as a creative tool in the digital design process to guide our own experiment.

**Fractal Geometry**

Fractal geometry arises from scientific research carried out by the mathematician Mandelbrot in the late 70’s. Mandelbrot found inspiration in the geometry of natural shapes, as stated in his famous words: "clouds are not spheres, mountains are not cones, coastlines are not circles, nor does lightning travel in a straight line" (Mandelbrot 1983). Disposing of fast computers with powerful graphic resources, Mandelbrot started to simulate those objects digitally.

A fractal is a mathematical object generated with geometric rules and it can be linear or non-linear. Fractal shapes can be generated by a system of similarity progression subdivided endlessly. One of the outstanding features of this geometry is that simple rules can generate very complex objects. Fractals are generated by a process called iteration, in which a rule substitutes each segment by a similar object, in other words, is the repetition of a block of actions in a computational program. Recursion is the reapplication of a function to the result of its own application. In other words, it is the repetition of a process that results in auto similarity. In a recursive method the solution of a problem depends of the solution of smaller parts of the same problem.

The Minkowski curve is an example of recursive function in which an initiator is divided in four segments with the same size. The two segments in the middle are replaced by two squares; the first one without the base and the second one without the top, iteration 2 of Figure 1. The iterative process continues infinitely.

![Minkowski curve](image)

One of the contributions of fractal theory to architecture is to create geometric patterns with gen-
Some architects have used fractals in the design process of projects and were used as references in the present research: SOM’s King Abdul Financial Center (Katz 2012), Daniel Libeskind’s Victoria and Albert Museum Extension, Heneghan Pen’s Egyptian Museum, Jean Nouvel’s Louvre Abu Dhabi and LAB Architecture Studio’s Federation Square (Burry and Burry 2010). In general, fractals can grow in endless iterations, but, as seen in the above examples, the number of iterations is limited when one wants to implement this geometry in design.

An example of using fractals as a generative system in an architectural design studio taught by Peter Eisenman was described by Yessios (1987). In that studio fractal geometry was chosen as a concept for the design of a biology center. Due to the difficulties in implementing a graphic computer program back then, the instructors had architecture and computer science students working together. The implementation of fractal algorithms in computer can be positive to the creative design process. Schmitt (1987:104) explains how fractals can be useful: "[...] the use of function oriented programming, and the application of fractal algorithms in the description and generation of design are important steps in understanding the design process".

**Ornament**

The understanding of detail in contemporary architecture has changed in the last decades (Moussavi and Kubo 2006; Picon 2013). During the Modernist period architectural detail was often designed in a way to hide itself (Ford 2003), or, as explained by Picon (2013:23) "the tectonic proved far more important to the Modernist project than the scattered ornamental elements that survived Loos’ condemnation". Still, details and ornamentation did not completely disappear. The materials and effects produced by them (e.g. concrete molds) started to be part of the architectonic vocabulary of architects such as Mies Van Der Rohe, Le Corbusier and Oscar Niemeyer. During the Post-modernism period the discussion about ornament became again very present in architectural theory. However, "typology, composition and their symbolic potential presented far more pressing issues" (Picon 2013:25).

Today, behind the Hypermodernist philosophy (Picon 2013; Lipovetsky 2004), the new ornament in architecture is directly linked to the ubiquitous use of computers and computation in the design process and production. As Picon (2013:26) observes: "it’s possible to generate textures and patterns with previously unknown ease. Complex geometries have become accessible to anyone who knows how to use a computer". But it is not only the ease of instruments that has fostered the revival of ornament; there is an interest to create complex surfaces and to enhance the building envelope. The contemporary detail plays a central role in the development of the project and becomes even more significant when aided by digital fabrication. Picon (2013) adds that "the proliferation of developments in design software has enabled architects to experiment afresh with texture, color, pattern and topology". Emmitt, Olie and Schmid (2004:16) also state that "presently we are experiencing an enormous amount of technological development, a race towards complete automation [...]", especially with the use of CAD and CAM resources in the specification of architectural details. Digital output allows manufacturing different parts with the same efficiency as standard parts. The materials and manufacturing equipment are also more present in the design process of architects demanding a specific detail.

The contemporary ornament has some typical features as stated by Picon (2013): it usually appears as superficial textures or patterns, and the movement of the façade becomes ornamental. The contemporary program of the building also leads to a more ornamented surface. According to Moussavi and Kubo (2006), contemporary architectural programs with flexible spaces and façades without openings enable greater attention to the ornament. For Schumacher (2009), "[p]atterns might serve purposes of decorative enhancement, feature accentuation, camouflage, totemic identification, semiotic differentia-
tion, or any combination of those. Architectural patterns are a potent device for architectural articulation".

Kolarevic and Klinger (2008:12) believe that materiality is one of the main characteristics of contemporary architecture: "[...] in contemporary architecture, materials and their inherent properties are often fundamental points of departure for discovering and exploring new spatial possibilities (effects) and for designing different perceptions and experiences of architecture (affects)". Recently, contemporary architects have realized that digital information can be used in manufacturing and construction by sending files to CNC cutting machines, for example. With digital manufacturing it is possible to construct more complex shapes and the ornamentation can result from geometric patterns and mathematical functions.

Gleiter (2009) concludes that the "[o]rnament is practically the intersection or interface between the technical and constructional processes that the material requires and the manual and creative processing through the craftsman or producer. [...] In the ornament both the material-constructional and the anthropological aspects become one as visible presence". The new ornament could be considered as a consequence of digital tools and production equipments, but also as a cultural response to a contemporary hypermodern society demands. As part of the society demands, the changes in technology have taken architecture to a high level of sophistication in terms of digital fabrication.

**Digital fabrication**

Architectural design has undergone major changes since the 70’s. Those changes were required by the complexity of architectural programs and the need to accelerate the design process. Recently the incorporation of algorithms in the architectural design process is becoming ubiquitous (Terzidis 2006; Kolarevic and Malkawi 2005). Algorithms can be generated using textual or visual computer programming, allowing designers to establish a strict procedure that can be applied from concept to detail. Besides, algorithms allow architects to better understand problems and find new methods to solve them.

Parametric design enables rapid exploration of solutions, because it is relatively easy to change the input data or other parameters. Furthermore, the architect acquires greater control over the models, analyzing them from the initial stage (Kolarevic 2003). The contemporary methodologies of architectural design are in fact new methods in which the designer is immersed in computational environments. Architects working with these methods usually express the whole cognitive design process (not only the final product), and explore parametric design and use programming to create relations between objects (Tidafi and Iardonova 2006). The form can be also easily modified by the manipulation of parameters and each design alternative can be tested to respond environmental, ergonomic, economic or structural demands (Meredith 2008). The alternative for the form and the parameters definition will strongly depend on the architect’s cognitive sensibility.

In digital design the cognitive abilities can be enhanced by the use of computational tools and mathematical and geometrical resources. These resources may help to solve or organize very complex problems (Terzidis 2006). It is important for the architect to know how to make basic algorithmic operations like "arithmetical, logical, combinatorial, relational, and classificatory arranged under specific grammatical and syntactical rules" (Terzidis 2006:38).

New technologies aid the design and fabrication/construction processes, offering new challenges to the designer. For example, nowadays it is common that parts of the building are fabricated individually and then assembled. The reduction of the construction time makes that kind of industrialization valuable because different parts of the building can be fabricated simultaneously. Iwamoto (2009:7) affirms that "[p]ractically speaking, because buildings are made from a series of parts, their assembly relies on techniques of aggregating and manipulating two-dimensional materials".

As new equipments are being incorporated to the production of buildings - CNC machines, robotic
arms, 3D printing, and laser, waterjet and plasma cutting machines - the architectural forms demand new methods of design. These equipments are used by a large number of industry sectors, from bicycles to airplanes, but are still new to construction. So, digital fabrication demands from architects the knowledge of programming and to be aware of how and which equipments will produce the design. The construction of more complex forms in architecture is possible with the use of digital tools and fabrication.

**DESIGN METHOD**

In order to test a design process with the use of fractals from conception to production, a project was developed as a proof of concept. It consisted of a sunscreen for the façade of a curved building that has been recently designed for Unicamp's main campus in Campinas. A parametric model of the building was developed with Rhinoceros (a 3D modeling software) and Grassshopper (a visual programming environment). The software 3DMax was used for rendering images. The equipments used to manufacture the models were laser cutter machines (40w and 100w) and a three axes CNC Router with a vacuum table. Since the building's structural design is still under development, it was important to develop a parametric model for the façade, so that any dimensional change could be easily made. The advantages of developing parametric models for advancing the detailing of a building whose dimensions are still not final has been stressed by Sheperd, Hudson and Hines (2011).

Grasshopper has an application that was important for this research: Hoopsnake, an add-on that allows the creation of iterative algorithms. Hoopsnake repeats an algorithmic procedure from a set number of iterations. The component creates a copy of data received from the user and stores it locally. This duplicate data is made available via a standard output parameter. We also used Autodesk Ecotect software for solar gain analysis, shading and thermal performance in the preliminary analysis.

It was noted that the control of heat stroke should be studied carefully and that any solution to sun protection should allow for ventilation efficiency. The curved façade of the building facing southwest resulted in areas of lower solar incidence and others in greater need of protection according to the season. This project was developed by two graduate and three undergraduate students for an elective digital fabrication class at Unicamp. The design process started with a main idea, then project and concept references were researched.

The architectural premise was based on case studies and references of façades protection as the *muxarabiê* or *muxarabi*, a type of façade element common in Arab architecture. The *muxarabiê* is often constructed with a regular design; in our case we use a recursive fractal pattern that allows irregular variations in the design.

The first step was to establish a parametric model of the building for the preparation of analyses. Taking the simplified virtual model as a basis, analyses were performed in Ecotect. Figures 2-4 shows the shaded region and the area to be protected during the critical period of 5pm in summer and winter respectively. In winter it can be seen the diagonal shadow generated by the building itself.

The virtual model and the general project files were planned for the production of drawings for laser cutting and to prepare a paper physical model. After the completion of the analysis of insolation and the construction of the model (figure 5), we discussed the proposal for the façade.

Figure 2
December 23th (top), June 23th (bottom).
The initial idea was to divide the façade in modules defined by floors and pillars, also creating a division of the façade (Figure 6). Recursive iterations could help to split the parameterized objects into smaller parts where there is higher solar incidence, creating more elements to produce shadows or voids. So, fractal geometry proved itself useful since it controls the iterations of elements at different scales, creating an auto similar pattern. The pattern variation obtained was associated with areas of more or less need for light.

At this time the project was still on a very abstract level and we did not know how the fractal elements would be materialized. However, any decision on how these elements could be implemented could be made by changing the parametric model. The first proposal for the façade was to divide it into macro panels each floor and each structural axis in a number of twenty-four. As can be seen in Figure 6 the proposed division intends to create diversity in each panel on each floor of each module, and is changed by the need for sun protection. That would reach a variation of design for individual macro panels and there would be a wider range of possibilities for mounting the panels on the façade.

Then we began the creation of parameterized fractal transformations with rotation and scaling of shapes. Points associated with planes at the virtual model served as coordinates to fractal generation. Four alternatives for the use of fractal in manufacturing the panels were created and are described herein with a nomenclature to relate them to the Grasshopper components: lines, pipes, planes and cuts (Figure 7). The lines were the initial fractal shapes constructed by connecting specific points of the façade panels and were iterated upon parameters defined by angles and rotation axes. The pipes were built with Grasshopper components of the same name, and were created using the lines as a center and a specified radius. Extrusion lines in a direction perpendicular to the panel, in which they are contained, created the planes. Finally, the subtraction of the pipes of a plane created a porous design (Figure 7).
The lines undergoing transformations created patterns that were tested and changed. The left lower region of the façade panels could be more open in relation to others, because of the shadow produced by the building, as seen in previous analysis. Both alternatives, planes and pipes, were simulated (as a single panel) to test the projection of shadow or light that would generate the pattern inside the building (Figure 8). The third alternative, planes, could function also as a light tray, but it would require a complex execution. The number of mating parts required would have been very high, which would increase the difficulty of assembling and would increase the weight of the panels. Another constraint of the overall design is that the façade do not have many places for fixing the panels.

Regarding constructive issues, the planes option would have a large number of parts and would be too difficult to maintain. The pipes option was also not selected because it would need tube bending machines (calendering) and welding and we would like to use manufacturing techniques that could be tested in terms of prototypes using the available equipment at the laboratory (3D printer, CNC machines and vacuum forming). The result of pipes in the façade would be similar to one of the reference designs, the Wuzhen Theater of Artech Architects. In this case, the façade elements do not perform as protection of insolation, but is an ornamental pattern.

Then, based on another project reference, The Orange Cube by Jakob and Macfarlane, we decided to use perforated sheets. However, we noticed that cutting the previously perforated sheets would not be the best option. Tests with the CNC machine showed that there would be problems with the deformation of the plate. Furthermore, the designed cuts would have a pattern of irregular edges.

The solution was to cut the plates and then perforate them. An algorithm that excludes drilling holes within areas of cuts and its edge was created. This maintains the integrity of the planned design and creates resistance on the edge of the hollow. Figure 9 shows the code that controls drilling applied in a part of the project, a parameter offset (in orange) controls the border that will be on the edge excluding the holes in this region. Grasshopper sliders control the amount of holes and their dimension. We also wanted to solve the design of the cuts to avoid the metal burr as seen in Figure 10. The plates as designed may be manufactured by any provider with
CNC machine tools.

So we analyzed the execution of the panels. Figure 11 is the design that varies randomly in each of the twenty-four panels; Figure 12 is the design of a single fractal for the entire façade. One issue that could hinder the implementation were the parts that come loose due to the crossing of the figures (larger white areas in figure 11 and 12), and the lack of rigidity of the plate caused by this geometry. This was noticed during the process, but became more evident when we produced a physical scale model made of laser-cut cardboard. In Figure 13 it is observed that the red part would be lost and the orange corners would become brittle. This problem was solved with the implementation of a detail that eliminates crossings through the creation of an edge.

Having solved the problems of the "loose" parts, lack of rigidity and drilling, some fractal alternatives were generated changing code parameters (Figure 14). Finally we choose an initial form of eleven lines that are generated on a diagonal that crosses the façade from the upper left corner to the bottom right corner. In the lower left corner of the façade there is less solar incidence, so in this area we could concentrate more hollow panels. The team decided to selecte the option B that appears in red. With the final design set, we then started the adjustment of the cuts. The models were produced at different scales to study the relations of the project; with paper in a laser cutting machine and aluminum on a CNC 3-axis router (Figures 16 and 17).

The final proposal was designed, modeled and tested again (Figures 15 and 16). Each of the 24 macro panels were divided into 5 smaller panels, positioned vertically, totaling 120 pieces. A detail of one of the panels can be seen in Figure 17.

Renderings (Figures 18 and 19) of one of the rooms in the building at different times of the year were produced, to check the visual effect inside the building and also the expected reduction of solar incidence without reducing lighting. Later, with the definition of the type of windows, this model can be further tested and changed if necessary.
Figure 14
Five variations of fractals with different transformations

Figure 15
Detail of the final proposal

Figure 16
Physical model with the final proposal in laser cut paper
DISCUSSION
In this study, algorithms were used at different stages of the design process, in an integrated process that involved the definition of the overall form and the resolution of fabrication issues, back and forward. The parametric environment allows the generation of various alternatives from the same algorithm by small changes in the data. In this way it was possible to carry out a process of design with the contemporary approach described by Tidafi and Iordanova (2006) that suggest that in addition to exploring different formal solutions, it is important communicate throughout the design process.

It is noteworthy that many necessary adjustments in the project were perceived only with the production of the models, such as changes in general measures, proper drilling spacing and the creation of a security edge around the cuts. The continuation of this process would lead to the creation of production-ready files (file-to-factory) with CNC tooling and further tests using Ecotect. The size of the holes in the plates can be variable through implementation of a control parameter. The production of a few prototypes would eliminate any problem of adjustment. After visits to manufacturing façade panels companies it was possible to note that the completion of the process would have required more collaboration among professionals, probably involving engineers and manufacturers of metal panels. Finally, we concluded that fractal geometry was indeed a tool that contributed to the creative design process and that could effectively address the contemporary ornament.

ACKNOWLEDGEMENTS
We thank CAPES for Maycon Sedrez’s PhD scholarship and FAPESP (Sao Paulo Research Foundation) for supporting the Laboratory for Automation and Prototyping for Architecture and Construction and this research (Process 2012/10498-3).

REFERENCES
Burry, J and Burry, M 2010, The new mathematics of architecture, Thames and Hudson, New York
Lipovetsky, G 2004, Os tempos hipermomemdos, Barcarolla, São Paulo
Meredith, M (eds) 2008, From control to design: parametric/algorithmic architecture, Actar, Barcelona
Moussavi, F and Kubo, M 2006, The function of ornament, Actar, Barcelona
Ostwald, M 2001, "Fractal architecture": late twentieth century connections between architecture and fractal geometry, Nexus Network Journal, 3(1), pp. 73-83
Ostwald, M 2009, Fractal architecture: knowledge formation within and between architecture and the sciences of complexity, VDM Verlag, Saarbrücken
Picon, A 2010, Digital culture in architecture: an introduction for the design professions, Birkhäuser, Basel
Picon, A 2013, Ornament: the politics of architecture and subjectivity, Wiley, London
Tidafi, T and Iordanova, I 2006 'Experimental approach in an architectural design studio - how digital technologies could change a design process', Proceedings of 24th eCAADe, Volos, pp. 852-858