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# Parametric Modeling: An Advanced Design Process for Architectural Education

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*The first part of this paper is giving an overview, experimentation results and feedback of a six years experience of parametric design education in schools of architecture from France and Belgium. The second part addresses a structure of an advanced educational process of parametric modeling able to support architectural design praxis.*

**Keywords:** *Parametric design, Digital design, Form generation, Digital fabrication*

## INTRODUCTION

Parametric geometry modeling is a field studying algorithms that compute geometry (Kelly 2013). A major barrier concerns the level of effort necessary to implement the algorithms: "the task is foremost, the tool need only be adequate to it" (Woodbury 2010). Since 2003 and the release of a new parametric software like GenerativeComponents [1] or Grasshopper [2], the conceptual representation containing the algorithms can be achieved through visual dataflow programming language (VDPL) dedicated to 3D modeling. The amount of abstraction between VDPL and machine language is high enough to allow non-programmers to implement complex parametric 3D models. Users with basic knowledge of geometry 3D modeling can specify a sequence of relationships and operations to automate the construction of geometry in the form of links and nodes.

They do not require any textual programming skills whereas they can achieve the creation of complex 3D parametric scenes in short time span and "efficiently explore alternative forms without having to manually build each different version of the design model for each scenario" [3].

## OVERVIEW OF PARAMETRIC MODELING EDUCATION

The first part of this paper is giving an overview, an experimentation results and feedback of a six years experience of parametric design education in schools of architecture from France and Belgium. The second part addresses a structure of an advanced educational process of integration of parametric modeling and digital continuum able to support architectural design praxis.

### ***Cognitive operations and design thinking***

After the first digital age defined by productions such as *blob*, developed by the use of animate form (Lynn 98), we attend an evolution of production, tools and methods in digital architectural design. Among the different tendencies on digital architectural design, the parametric way has a specific place. Parametric modeling led to the development of a model that is not a single object, but the potentiality of a family of objects called instances. As teachers, we often attend to the same situation: at the end of the parametric design studio, some students cannot identify how they arrive to the solution. The main reason seems to be a gap between the knowledge application and the skills trained during the lessons. In fact, the most important problem is the lack of knowledge and skills about digital design in general and specifically about the digital design in architecture. The theoretical aspect of architectural design is still on a traditional way.

### ***Education context and technological mutation***

As we know, the last fifteen years are witnesses of a mutation of the architectural production through the improvement of digital design and fabrication tools. It is now more and more possible to overtake a situation noted by A. Picon (2010) about the rupture between free-form seduction and tectonics. This evolution is mainly due to a methodological threshold, which enables the integration of computational processes like parametric in the core of the architectural design process. We also attend an evolution of the structures closely linked to the matter and the continuity namely digital data transmission in the "design to fabrication continuum" of building elements, indeed the whole building process. To meet this transformation, teachings, should integrate a computational approach both theoretical and practical allowing the student to acquire a culture in contemporary architectural practices, knowledge and parametric modeling capabilities and reach an experience in the "design to manufacture continuum". At the prac-

tical teaching of the parametric, the crux lies in the transition from paper sketch to the parametric structure (Couwenbergh 2015).

### ***Design pedagogy and digital design concepts***

More precisely about the architectural design thinking, we have to point an essential notion: there are significant differences between traditional architectural design and the digital mediated design. We can say the digital design constitutes a unique body of knowledge and architectural concepts (Oxman 2008). Many researchers have proposed as a foundation for design education and pedagogy that digital design has an influence on the development of theoretical, computational and cognitive approaches. Seven years ago, R. Oxman wrote that "any new framework for design pedagogy must be responsive to condition in which digital concepts are integrated as a unique body of knowledge consisting of the relationship between digital architectural design and digital design skills". Designing and modeling free-form surfaces and curves as building elements that are associated with different components and have multiple patterns are not an easy job to do with traditional methods. This is the power of algorithms and scripts that are further pushing the limits (Khabazi 2010). Custom CAD tools are examples of lowest algorithmic level in design, and the parametric modeling skills are not capable enough. High level of parametric modeling skill means using the computational power in a design process. It is obvious that even to think about a complex geometry, we need appropriate tools, especially software packages, which are capable of simulating these geometries and controlling their properties. Before training these skills and using such tools, there are a few elementary theoretical basements to teach. As a first step in the education of digital parametric design, the historical approach is paramount to provide context on the one hand and on the other to highlight the concept of parametric, which existed long before the arrival of the computer. It is necessary to first address to the

origin of the terminology (parameter and parametric) questioning the history of science (Apollonius, Newton, Pascal, etc.), then take a look at its use in the arts (Dürer, etc.), architecture (Gaudi, Moretti, etc.) and structure (Frei Otto, Sergio Musmeci, etc.) (Couwenbergh 2015).

### ***Parametric digital modeling***

As we know, the defining feature of a parametric model is not the outputs but rather the need to construct and maintain relationships associated with the model. Some researchers develop this approach as the creation of process instead of formal product. In this design model, the visual representation is not a direct production from hand but appears as the result of a computational process in which the user has to manipulate geometrical concepts through a program (visual or textual). The student has also to be aware that the parametric model is defined by a set of heterogeneous elements (geometric or positional numerical constraints) put in relation to form a coherent whole (de Boissieu 2013) and the design logic of the model creates the complex relation sets as a network of associations (Oxman and Oxman 2013). Another topic, consequence of the latter subject is that the result of the computational modeling process is not simply a shape or an object but provides the possibility of a wide (or infinite) space of design solutions. The output variations can be achieved by the variations of the parameters included in the schematic structure of the model. In this way of thinking, we can say that the design method comes out of the linear and vertical design process only controlled by the architect. Every specialist steps in the first stages of the architectural project development. The last important prior information for the lessons is that the designer himself decides what parameters to use and what the range amplitude of the variations is the most relevant. In the next section of this paper, we will expose in our respective education how we explore different methods about construction of parametric design models and their outcomes, like the passage from sketch to logic model schema, the in-

tegration of material and structural constraints, or for example the capability in shape versatility.

## **AN INTEGRATED PARAMETRIC MODELING EDUCATION METHOD**

The second part of this paper proposes a process of integration of parametric modeling and digital fabrication in architectural to support design praxis. The proposed process is a result of our experience in parametric modeling education and research in digital design praxis. The proposed process is structured in three steps: analyze, implementation and experimentation. This process associates digital design and fabrication tools to physical representation and modeling tools as freehand sketching and makeup realization (Sanguinetti and Kraus 2011). It combines also mathematics, non-Euclidian geometry, fractal design and design knowledge to create a design process by iteration. This educational approach gives the opportunity to students to apprehend the many application fields of parametric modeling that go beyond the expected framework of algorithmically generated forms.

### ***ANALYSE STEP (MULTI-LEVELS)***

A parametric model is based on both an explicit representation of an object and a conceptual representation containing the parameters and the operations (Agbodan et al. 1999). It is a dual structure, with on the one hand the geometric shape and on the other hand the algorithm. But to implement the algorithm that in turn will compute the geometry, it is first necessary to analyze the intended shape in order to identify its parameters and the generative operations. The analyze step starts by the definition of the geometric, physical and logical operators and the entities characterizing the different features of the intended model. This process is based on the formalization of the geometrical knowledge required to design the parametric model. At first, the concepts of the field under study have to be named, structured and prioritized to aid in the organization of the knowledge of the domain. It defines a model that is a synthetic

and abstract representation of reality allowing a better understanding of it in the context of a determined purpose. This knowledge model identifies and defines every feature of a shape and its relationships with other features. Knowledge has to be modeled in order to make explicit the geometrical constraints (i.e. the relationships) that govern the spatial properties of the entities (i.e. the features) and linked them. Only then it is possible to develop the design rules that generated the final shape. Moreover, once the geometric knowledge of the studied object is modeled, it can be enhanced with semantic knowledge such as physical properties (acoustics, lightning, etc.) according to the purpose of the project (analysis, simulations and manufacturing). The analyze step is supported by sketching activities. Sketching as a free-hand drawing activity helps students to quickly represent the different step characterizing the modeling process (Schon 1984). They use it also to identify and characterize the major entities (geometrical, logical) used to materialize these steps. Using sketches, student can analyze the modeled object features and imagine different ways to create a parametric model of the aimed object (architectural or structural issue) (Gallas and Delfosse 2015). The drawing, the modification and the annotation of the sketching activity create an iterative process that supports the optimization of the parametric model (Sanguinetti and Abdelmohsen 2007).

### **IMPLEMENTATION STEP**

Architecture students are not intended to be expert on programming. They may, however, be considered as end-user programmers who "write computer programs to satisfy a specific need, but programming is not their primary job function" (Lewis et al. 2009). Since 2003, visual programming languages have become popular among design communities as they allow students to focus on the problem solving activities rather than on the syntax of the programming language (Giordano and Maiorana 2015). Thus modern CAD tools are very similar to flowcharts. They share a visual program syntax that uses geometrical

symbols to map the flow of relations from parameters through operations, decision, etc. (Marttila-Kontio 2011). In CAD, designers have to switch between the programming environment and the model view several times to make even the most simple modifications and evaluate their effects on the model, which results in a loss of focus and efficiency (Maleki and Woodbury 2010). The duration of the definition and the transformation of the parametric model depend on the designer knowledge level of parametric modeling method and tools. Experts users can reduce time spend on the parametric model generation and more focus on the design activities (supported by the generated parametric model). For novice uses, modeling activity is considered as an additive constraint that influences the design process. They spend the most part of their designing time to create the parametric model and not to operate it to support the design process. We propose a method (materialized by a physical device) to support the translation of the parametric model generation steps resulting from the analyzing step and materialized by sketches. We create a physical device called *parametric puzzle* integrating rectangular components (tabs) that describes the major geometric and logical entities used to describe the modeling process. Designers are asked to translate analyzed sketches representing the parametric modeling steps into a physical algorithm workflow very similar to flowcharts. This method allows a high level of modification and evaluation of the parametric workflow breaking away from the complexity generated by parametric modeling tools. Designer could generate different workflows and modify them to define the most optimized approach (using less number of entities and operations).

### **EXPERIMENTATION STEP**

Parametric modeling is often used to design and explore new architectural and structural solutions characterized by a high level of complexity. To achieve this task, the designer needs to evaluate the generated instances behavior and their ability to support

design constraints. The evaluation results helps designer to select the most pertinent solutions and by the way the most pertinent model parameters. The first experimentation level is a virtual evaluation realized using simulation tools and algorithms linked to the parametric model. The association of the parametric model and the simulation tools creates an iterative process structured on three activities: propose, evaluate and assess. Using the iterative process, the designer can integrate different design constraints (translated in logical, geometrical and physical operations) and propose a collection of optimized configurations. The second level of implementation aims to evaluate physically the behavior of the generated solutions. It is a confrontation step with the physical and material reality of the designed object. It help designer to determinate if the designed object could support the real constraints. The material experimentation is implemented by the realization of the project (or object) components and the evaluation of their behavior. The use of physical models and mock-ups is one of the most pertinent technics of material experimentation. Designers can visualize and physically evaluate if the designed object satisfies their intentions and verifies all the design constraints. They can modify and transform the physical model to ameliorate its performance or integrate new constraints. By this way, physical object is used as a design support device that influence and modify the parametric model to integrate the new features. The experimentation step is the lowest abstraction level of the parametric design process. At this step, the designer has all the information about the modeled object and its modeling process. These information are progressively defined through analyze and implementation steps. In the next part of this paper we will present some of the pedagogical experiences integrating (at different levels) this parametric modeling method.

### **METHOD IMPLEMENTATION**

The presented method is integrated in different courses and workshops of digital modeling and fabri-

cation from three European universities. We present the courses structures and purposes and how parametric modeling is integrated. The first institution is the faculty of Architecture of the University of Liège (Belgium) proposes for the fifth consecutive year an optional course in expression and communication, worth 2 credits within the framework of a two-year master program for Architecture. The course based on a previous experience developed from 2003 to 2005 (Bianchi and Defawes 2005), is intended to develop themes relating to formal and material research as part of the approach to architectural projects: it combines, digitally, the emergence of form, its control, and the media devoted to the materialization of designed objects (in their broadest sense). This relevant approach is reflected in the use of tools, which can aid design and lead to increased control over the project. In addition, the use of design assistance tools offers methodological opportunities. The analyzing step is supported by the integration of mathematical theories behind the research of architects concerned. The mathematical theories help students to define the morphological structure of the modeled object. The integration of mathematical concepts gives to students an analyzing context that simplifies the definition of the geometric operation and entities structuring the parametric model. The courses continues by introducing the students to the use of programming language used in the chosen modeling tool to generate complex 3D forms and to control them. Students learn to manipulate standard commands in architectural software packages, with a view to creating complex geometrical forms. The example integrated below (see figure 1) shows how parametric equations of wellknown curves are integrated to define the project concept and the parametric model features.

The second institution is the school of architecture of Nancy (France) that combines for the sixth consecutive year parametric design courses and a five-day workshop within the framework of a graduate program in digital culture for Architecture (Shadkhou and Bignon 2009). The course is indented to deepen the knowledge of students of methods and

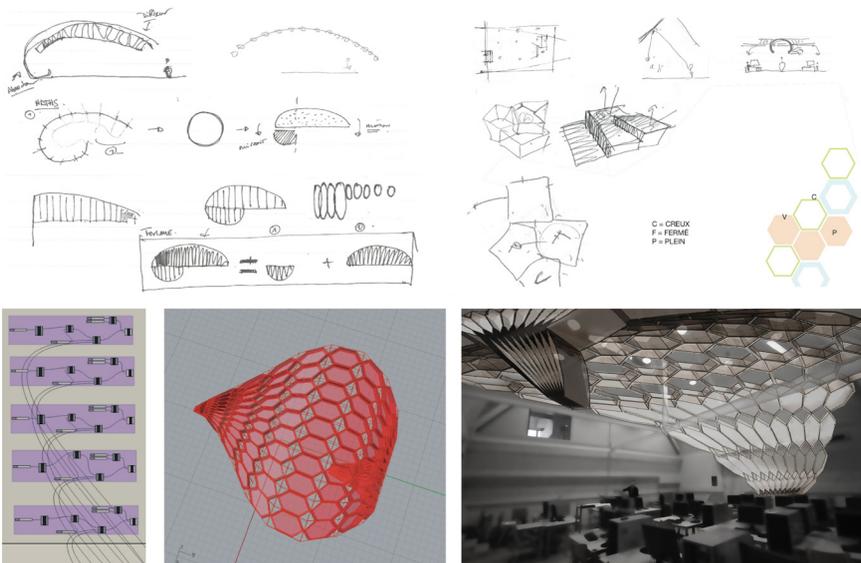


Figure 1  
Example of  
student's work  
using mathematical  
functions to  
generate the  
project shape

digital tools in computer-aided design through the use of new generation parametric techniques based on visual programming (Grasshopper). The workshop of digital design and fabrication, flowing the courses, is the spearhead of parametric education in the program. It tries to experiment contemporary architectural practices (non-standard architecture design and complex shape generation) using parametric modeling, 3D printing machines and digital fabrication devices creating a digital continuum from digital file to physical object (Marin et al 2009). The workshop creates a design process to enhance architectural shape exploration and materiality by using parametric modeling and digital fabrication tools. The students use a reference object (from the nature) as a base model to design an exhibition space. They identify the formal structure of the reference object and represent using sketches. The students use the

identified structure to propose an architectural solution and materialize it using parametric modeling tools. The designed response respects the functional and material constraints explained at the beginning of the workshop. The sketches (see figure 2) are used as a design tool to materialize the designed solution and define its different modeling steps.

In this way, the students participating on the workshop use simple paper model and more elaborated mockup to experiment the generated parametric model structure. They use the physical model to determinate how to join the project components. The result of this first experimentation was integrated in the parametric model by adding new geometric functions generating the assembling system. A second virtual experimentation based on 3D modeling help students to validate the assembling system and to start the fabrication process.

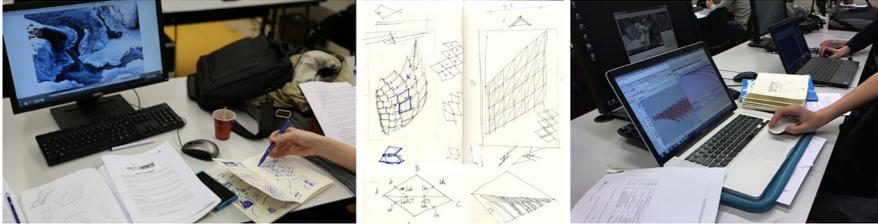


Figure 2  
The use of sketches  
as design and  
implementation  
media

The Faculty of Applied Sciences of the University of Liège and its Engineer-Architect Department (Belgium) integrates parametric modeling as a part of Computer Aided Design courses. We propose a design exercise where students used parametric modeling tools to generate original forms integrating structural and construction constraints (create an interaction between structure and form). It combines digital tools for modeling and fabrication tasks, and physical tools for the parametric analysis process. The analysis step comes before the modeling one to help

students to focus on parametric model structure and features and not on the use of the modeling tool (Davis et al. 2011). We use the *parametric puzzle* (see figure 3) as a main device to analyze the designed object and define the main parametric modelling steps. We imagine the parametric modeling exercise as a reverse design process. The process starts by analyzing a physical model (mock up) representing a pavilion with a complex structure shape. They identify the structure components and tries to imagine how they could be designed. Sketching activity is used to



Figure 3  
Physical model  
experimentation  
and mock-up  
realization

represent modeling process steps as a high-level abstraction activity.

The defined modeling steps are materialized using the *parametric puzzle* components. The students used it to translate the sketches in as graphical algorithms integrating geometrical and logical entities as a middle-level abstraction step. The device helps them to generate different ways of modeling and to select the most pertinent. The last step of the modeling process integrates the translation of the graphical algorithm using physical components to a graphical algorithm using Grasshopper components as a low-level abstraction activity. The use of the *parametric puzzle* as a parametric design device help students to create different levels of abstraction during the parametric modeling process.

## CONCLUSION

This paper presents an advanced design method adapted to pedagogical architectural design context. The proposed method is structured in three

major steps: analyze, implementation and experimentation. We integrate different pedagogical devices to support the proposed method activities. The method activities and devices were evaluated in different design contexts to determinate their efficiencies. The evaluation of the project realized with students from the Faculty of Architecture of the University of Liège (Belgium) shows that the integration of the mathematical theories during the analyze step helps them to define the structure of the designed models (not only the project form). The designed models are well optimized generating controlled forms and including reversibility functions. The use of the *parametric puzzle* device was experimented during the digital modeling courses of the Faculty of Applied Sciences of the University of Liège (Belgium). The group of students using this device understands quicker the parametric modeling method and how to use it in real design context (compared to students from precedent years). They use this process to analyze other complex design context and to define

Figure 4  
Students using the  
parametric puzzle  
device to define a  
parametric  
modeling process



(quickly) more efficient parametric models. The integration of the prototyping devices during the experimentation step helps students to integrate material constraints during the design process. This process was experimented during the digital design and fabrication workshop organized by the School of Architecture of Nancy (France). The evaluation of the designed projects and the design process shows that the integration of experimentation activities and devices create an exchange between design and material. This integration process generates new design solutions and a new materiality. This method is part of a global research work that aims to enhance the integration of digital design aid methods to create a digital continuum from concept to physical object. The next step is to define an optimized process for the integration of the digital continuum in design studios.

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