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Research

Interlocking, Ribbing and Folding: Explorations in Parametric Constructions

Abstract. This paper presents three projects involving the design and fabrication of architectural structures through the use of different parametric software and digital manufacturing methods. The first project is a flexible partition composed of interlocking elements shaped using a laser-cutter. The second project is a university exhibition unit made with various wooden panels manufactured through a computer numerical controlled (CNC) system. The third project is a system of metal sheets folded by digital machines to create urban circulation spaces. The three works develop a parametric programming of geometry based on certain technical factors, enabling the recognition of patterns of interaction between formal and constructive issues involved in the definition of shapes through parametric controls. Differences in materials and processes are contrasted by similarities of function and conditions involved, creating a system of local, global, productive and environmental parameters that produces a repertoire of self-similar dimensions and variations as well as multiple possibilities of initial setups and final configurations. It suggests a specific field of design exploration focusing on the development of differentiated components and variable architectural configurations, in a kind of open parametric system.

Introduction

The consideration of technical aspects early on in the process of architectural design has traditionally been considered a necessity for developing proper solutions, but also represents the possibility for promoting creative alternatives. Works by Antoni Gaudí, Frei Otto, Eladio Dieste and Santiago Calatrava are frequently cited as key examples where architectural forms have been conceived through innovative structural and constructive considerations. Nowadays the management and performance of building construction has become substantially more detailed, influencing the constraints, products and complexity of buildings. This necessitates a closer relationship between technical conditions and architectural shape, through design strategies that combine them to support creative explorations.

Parametric design software makes it possible to control numerical aspects of the definition of shapes, establishing mathematical relationships between geometry and varying conditions. Several examples of architectural designs have shown the use of parametric software for the integration of different requirements (technical, environmental, functional, etc.) or specific evaluation criteria [Meredith 2008]. The application of this technology during the initial stages of architectural design permits the exploration of multiple possible solutions within determined constrains [Shea et al. 2005]. Nevertheless, no overall design strategy based on these technologies has been fully

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defined with regard to the relationship between different factors involved or their specific architectural possibilities.

This paper presents three projects carried out by the authors in the design and definition of architectural structures through the use of different parametric design software and digital fabrication methods, reviewing similar conditions in order to identify common design processes and technical aspects involved.

Design parameters can be considered on diverse levels of a project to define particular elements, to control overall form, to control production constraints of elements and design features, and to respond to site conditions that are determinant for several aspects. A conceptual structure of four types of parameters is proposed: production parameters (PP); local parameters (LP); global parameters (GP); and environmental parameters (EP). These categories make it possible to recognize interactions between the factors taken into consideration in the definition of shape in the projects presented.

Project 1: Pixel-Wall

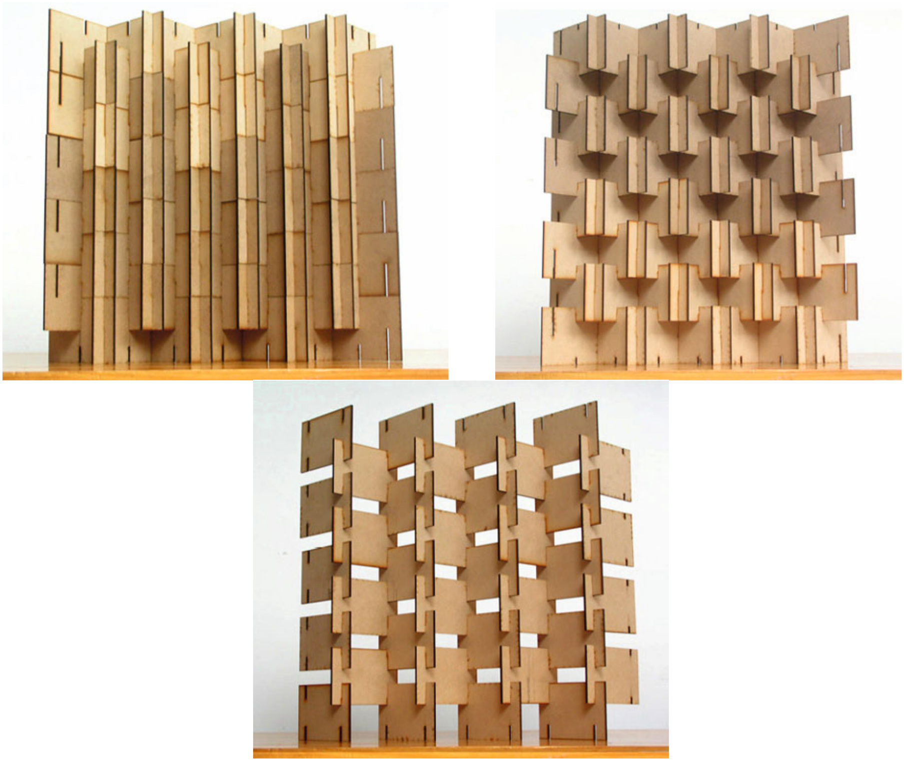

Fig 1. Initial scale-models of Pixel-Wall

Research into a system composed of interlocking plates (called "Pixel-Wall"), was initiated in mid-2009 at the Universidad del Bio-Bio, in Concepcion, Chile by researchers Rodrigo Garcia Alvarado, Underlea Bruscato, Oscar Otarola and Karina Morales.

The system was initially developed on industrial medium-density fibreboard (MDF) boards subdivided into regular elements measuring 61 x 38 cm. (sixteen per panel) to fit within the maximum work area of a medium-size laser cutter. Slots for assembly purposes are cut from these rectangular pieces, to permit interlocking at perpendicular angles. This makes it possible to generate a sequence of interlocked plates which are assembled with other sequences of plates to produce a three-dimensional lattice. Because of the width of the pattern, this configuration is capable of being structurally self-supporting. This arrangement of plates also combines visual enclosure with inner openness, allowing ventilation and indirect illumination, as well as having an expressive appearance and the possibility to hold small objects.

A vertical lattice can be used as partitions or decorative panels. Constructed in more permanent materials, it can be used for outdoor fences, acoustic barriers or ventilated facades. Used horizontally, it can be used for permeable roofs or full envelopes, with varying shapes, transparency, ventilation and noise reduction.

The structural capacity of this configuration is increased by the introduction of curvature in the general configuration, which also allows more formal variety. The inclination of the lateral grooves can create transversal curvature, depending on the angle and length of each slot. In turn, the change in the position of the lateral grooves in the edges can develop a longitudinal curvature (although this stresses the plates). The inclination of the main grooves produces a torque plate that develops curves in both directions. These minor changes in the geometry of each plate result in major modifications in the arrangement. Further, to obtain certain general overall shapes, it is necessary to determine the specific conditions of slots.

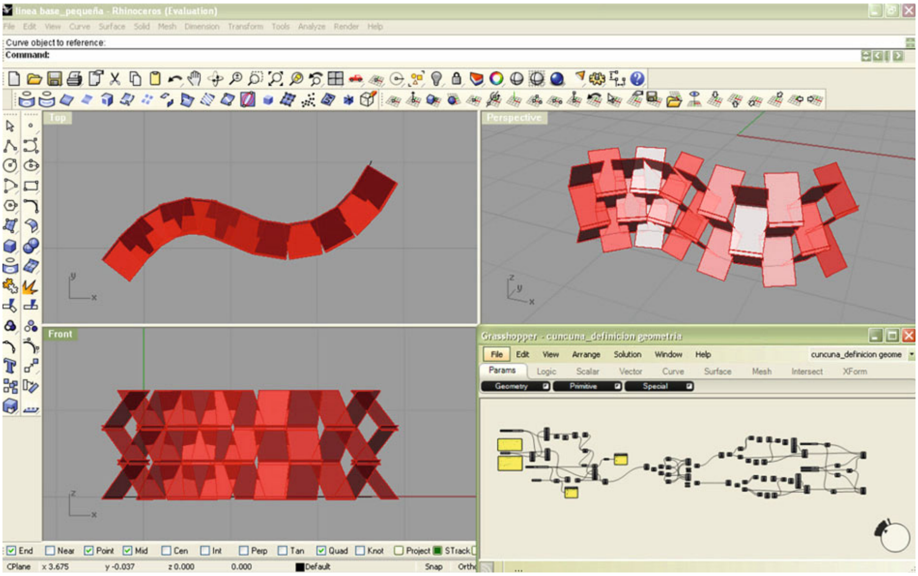

Fig 2. Parametric programming of curved designs of Pixel-Wall

The geometrical relationship between overall configuration and the slots of the panel was implemented through parametric modeling software (Rhinoceros with Grasshopper™). It establish the path of a curve as the axis of the vertical arrangement to develop the plates interlocked according to different amount of pieces in length and height, as well as diverse sizes to regard several materials. The programming makes it possible to generate the complete profiles of the pieces and their respective slots for cutting.

Several full-scale installations of the system have been carried out to test design and execution. For example a decorative partition was installed in the university hall (fig. 3), based on a spline curve 9 meters long and 1.6 meters high, using 160 plates cut from ten MDF boards. This installation was executed in two days and assembled in a couple of hours. The same pieces were used to assembly other configurations, such as curved coverings.

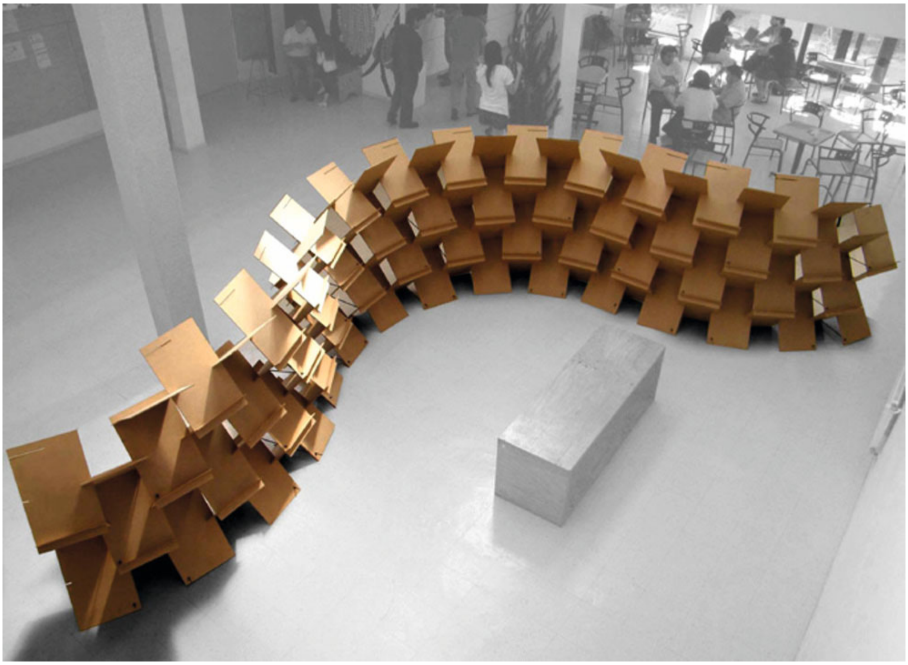

Fig. 3. Installation of Pixel-Wall

Project 2: UMBRALES 2009

The exhibition "Umbrales 2009", held at the Pontificia Universidad Catolica de Chile in Santiago, was a design exercise built at full scale, which was developed in an academic Workshop led by Arturo Lyon and Claudio Labarca. It took as a starting point the definition of specific relationships between the spectators' angles of vision and the variable angles of inclination of the supports for the exhibition of a selection of models and drawings of projects carried out by the students during the previous year.

These relationships were established based on a parametric display module, producing multiple variations in response to changing viewing conditions and to the different kinds of materials exhibited. This system was parametrically modeled using the software Digital Project™, establishing a series of ribs of equal topological conditions, whose angles and dimensions could be adjusted in response to a local geometric mechanism reacting to changes in global parameters. The original module was replicated to produce the entire aggregation, which consisted of 160 different modules and was capable of adapting to changes in the controlling parameters of the overall organization, adjusting their angles and internal dimensions accordingly.

Each rib had to respond to varying angles on the two supported boards, so that it was necessary to include a local scripted reaction to evaluate neighboring supports and determine whether an individual rib was ascending or descending in relation to adjacent ribs, triggering the activation of the corresponding geometrical solution. These changes are translated simultaneously as updates to the manufacturing drawings generated from the three-dimensional model. Each component is composed of seven parts: four segments and three joints. The 1,120 individual parts were cut by a CNC (computer numerical controlled) Router, and then coded and assembled on site.

The exhibition was installed in three different places, with the arrangements changing according the spaces provided, the flow of visitors, and illumination. It used different lengths of series and layouts to create a combination of materials displayed based on the planned exhibit itinerary.

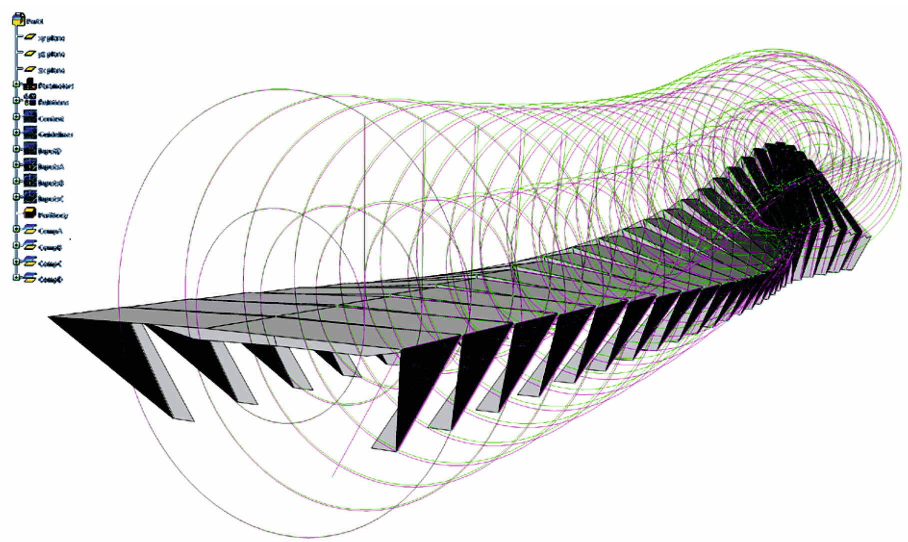

Fig. 4. Parametric Design of Umbrales 2009

Fig. 5. Elaboration of Umbrales 2009

Fig. 6. Installation of Umbrales 2009

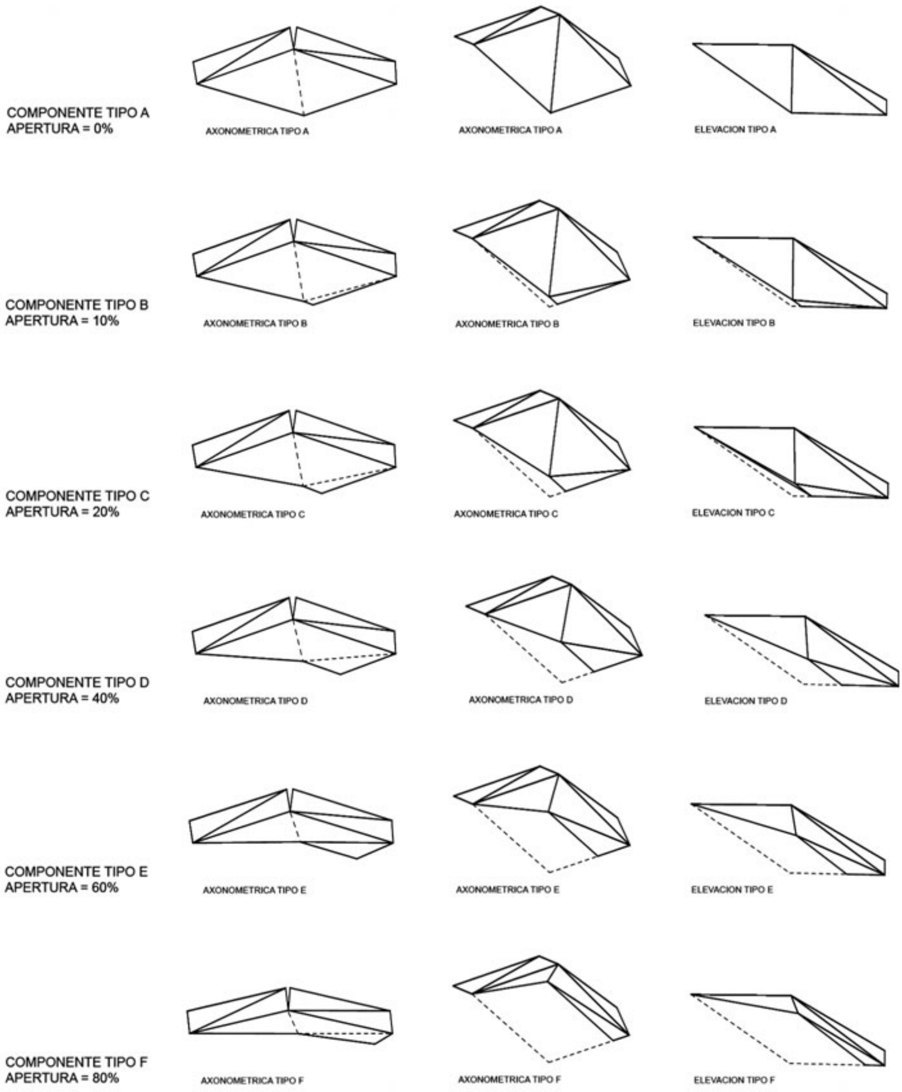

Fig. 7. Parametric design of Plega

Project 3: Plega

The exploration of two architectural projects based on the design of a structural skin system was carried out by Arturo Lyon with collaboration of AKT (Adams Kara Taylor Structural Engineers) and Ivan Valdez in 2008-2009. The skin is composed of aggregations of diamond-shaped components built by folding thin metal sheets (0.7 mm. to 2 mm. thickness), which are cut and folded into rigid three-dimensional panels. The structural quality of the components is provided by resistant edges formed by the folds, reducing the distances of buckling of the sheets while defining a mesh to distribute stresses across a continuous surface.

The Plega system can be adapted to planes or to surfaces of single and double curvature through the use of two-dimensional arrays of parametric components that adjust their internal configuration, while always maintaining the faces coplanar with its four immediate neighbors in order to adapt to non-homogeneous surfaces determined in relation to specific contextual and programmatic conditions. The local variation of the degree of opening of the skin is defined by structural and permeability criteria according to the position of the component in the overall configuration. These local parameters are controlled by data spreadsheets associated to the parametric models developed in the software Digital Project™.

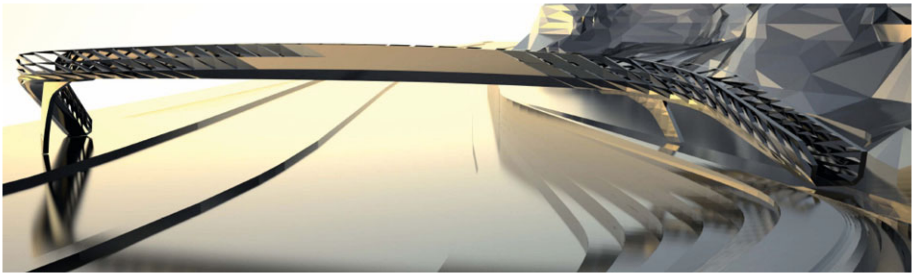

Fig. 8. Application of Plega in a footbridge

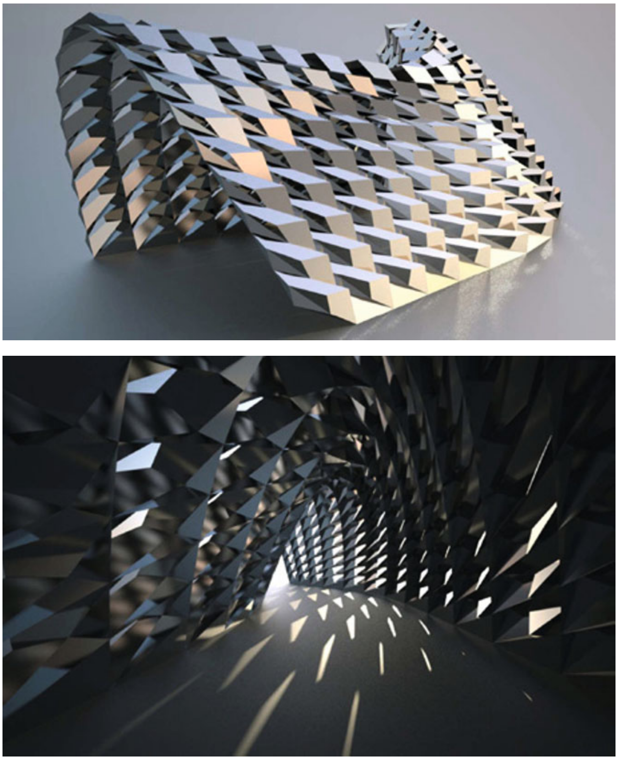

Fig. 9. Application of Plega in a pavilion. a, above) exterior view; b, below) interior view

Plega footbridge. In this project the Plega structural skin system was exploited to bridge a span of 40 meters, forming a footbridge that crossed a highway and provided access to a nearby public building (fig. 8). The structural system was designed based on a resistant shell made of a series of fifty inverted arches in the shape of an U. This sequence of components was adapted to the overall defined configuration by integrating specific contextual conditions on the connecting edges of the footbridge, its continuity with preexisting paths and traffic restriction.

Plega pavilion. This temporary pavilion for the Biennale of Architecture in La Paz, Bolivia, was based on a vault made of fourteen interconnected catenary arches with eighteen components each (fig. 9). The proposal at the urban level was to create a shortcut between two busy pedestrian flows, orienting the path between the square and public building that contained the exhibitions of Architecture Biennale. This project was tested through parallel prototypes using CNC machining for cutting and folding of 2mm. thick metal sheets and by printing plans to produce cutting guides for traditional hand tools using 0.7mm. thick metal sheets.

Analysis

Similar conditions ascertained across the three projects described above, developed independently by the authors of this paper in association with different collaborators, make it possible to define common characteristics of parametric design and fabrication processes (Table 1). Although materials (MDF boards, plywood boards and metal sheets), manufacturing methods, processes and dimensions differ, all three projects featured industrialized boards of regular dimensions of about 2 x 1 meters which were manufactured using digital-controlled machines, dividing them into parts smaller than one square meter, with differentiated configurations that allow for the formation of three-dimensional spaces.

The components implemented were variously shaped (rectangular, longitudinal or diamond), and specific details were drawn up to establish up their assemblage (slots, supports and folds respectively). The elements had different configurations, thicknesses and treatments, but in all three cases the individual parts worked jointly to achieve their tectonic qualities as well as their capacity for bearing weight and dividing spaces. The limited structural resistance of these materials, the result of their being mostly intended for decorative use, is augmented by exploring configurations that can result in higher bearing capacity despite their relative thinness (less than 20 mm). They perform by transmitting planar stresses between the elements in different ways (compression, bending and shear) favored by overall forms and connectivity conditions, developing three-dimensional distributions of variable loads, behaving in all three cases as space structures.

The capacity of the components to perform as partitions is mainly a result of opacity and the ability to support lightweight graphic material, which are achieved by the industrial properties of the material defined to fulfill similar purposes. Environmental protection is porous and related to semi-enclosed space, intended as temporary structures that do not need to provide complete protection, since they remain permeable and do not comprise additional elements to achieve acoustic or thermal insulation. Although they performed relatively temporary, non-specific and simple roles, no easy ways to improve these aspects has presented itself, and their nature as an aggregation of individual interlocked elements makes achieving such characteristics complex. On the other hand, they exploit the capacities of materials in their original states, without adding finishes as is usually done, but relying on repetition and continuous variation to define textures through the slight interstices between components. The original treatment is made evident from different viewing angles and light conditions, and through variable volumetric formations, deploying a wide range of spaces with a remarkably efficient use of materials to give a considerable constructive effectiveness.

	PIXEL-WALL	UMBRALES	PLEGA
Element			
Material	*MDF boards*	*Plywood*	*Metal sheets*
Fabrication	*Laser cutter*	*CNC Router*	*Industrial Cutter*
Shape	*Rectangle*	*Lozenge*	*Diamond*
Size	*61 x 38 cm*	*Variable*	*Variable*
Thickness	*6-9 mm*	*12 mm*	*2 - 0.7 mm*
Assemblage	*Slots*	*Supports*	*Folding*
Variations	*Length of slots*	*Inclination*	*Angles & Opening Size*
Finishing	*Reconstituted Wood*	*White sheets*	*Shiny steel*
Composition	*Rows of couples interlocked*	*Ribs of modules with 4 segments and 3 joints*	*Skin of folded pieces*
Design Software	*Rhino-Grasshopper™*	*Digital Project™*	*Digital Project™*
Applications			
Properties	*Partial Opacity*	*Support of Graphic Material*	*Covering or Structural Span*
Functions	*Partitions*	*Exhibition Display*	*Circulation*
Constructions	*Indoor Installations*	*Academic Exhibition*	*Pedestrian Tunnel and Bridges*
Dimensions	*12 x 3 m.*	*2.20 x 80 m.*	*4 x 12 m / 2.5 x 40 m.*
Location	*University Hall*	*Cultural Centre*	*Public Entrance*

Table 1. Comparison of Projects Developed

In all three cases the development process consisted of few operations, although more complex than usual because the differentiated elements required more elaborate design instructions and naming systems, which in general terms allows for a significant reductions of time and management in production. The three projects comprise at least two architectural applications (considering that Umbrales exhibition consists of different exhibition modules, which can also be used in different situations) in which the different versions articulate various spatial configurations while maintaining formal similarities due to their construction system. In this sense the different cases use variable components and different architectural configurations, thus comprising an open system rather than the design and implementation of a particular building.

Elements and designs define formations that escape conventional solutions, especially because of their lack of regular modulation. The projects carried out were temporary and lightweight constructions suitable for experimentation, and did not take cladding, services or internal configurations into consideration. These developments and their results show common conditions that express a methodological procedure and open a new field of architectural possibilities based on digital design and manufacturing technologies.

Parameters

Regarding the categories of parameters suggested earlier, in these cases the local parameters (LP) are mostly the shape and dimensions of the components, which varied to produce constructive connectivity with neighboring parts (relations between components), production possibilities (size of the original elements) and spatial potentials (size of enclosures). To a lesser extent, the materials vary locally, according to properties of resistance and insulation determined industrially, which define quantities and qualities of spaces. Finishes, patterns and size are the main expressive qualities of the configurations.

Global parameters (GP) are essentially the overall dimensions of the enclosure spaces, which determine the amount of components (according local parameters), with a formal subdivision that contributes to general capacities for resistance (curved or diagonal distributions) and takes into account functional capacities (internal sizes). Generating a global spatial formation with semantic, functional and environmental conditions, based on certain outdoor properties as environmental parameters (EP), such as the dimensions of the usable site, orientation, regulation, visual projection, functional relationship, and urban or historical references, to determine the overall characteristics of form.

Production parameters (PP) refer to specific restrictions of dimension involved in the fabrication process, which are determined by the size of industrial products used and the work areas of the different CNC machines used. Along with a repertoire of specific commercial products with different technical capacities and available finishes, this aspect is also affected by the technical skills of those producing the components and carrying out the assembly, and specific circumstances for implementation (transport, setup, etc.).

This combination of factors determined the architectural configurations, some of which were implemented through parametric programming, with a few alternatives tested on physical prototypes, making evident the field of possibilities implicit in the projects and the need to control the formal relations and techniques involved.

A conceptual scheme of parameters at the different levels is given in Table 2. This diagram is neither exhaustive nor precise, but helps illustrate how interaction between several characteristics of work can be managed in parametric design. In production parameters (PP) there are many physical properties of material or manufacturing conditions. Local parameters (LP) regards the piece manufactured, and usually involves defining several features based on the physical properties of the materials combined with the geometrical dimension or shape. Global parameters (GP) regard the main characteristics of the design, usually based on sections or group of components, and several interior properties based on features of the elements related to the space configured. Environmental parameters (EP) regard some conditions of site which constrain total volume, situation and features. Many of these features are not easily converted to numeric factors or geometrical relationships, due to the use of different units or the presence of complex conditions. However, it allows us to see how some specifications can be managed to establish an open design system.

PP- Production Parameters	LP- Local Parameters	GP - Global Parameters	EP - Environmental Parameters
Dimensions of industrialized material			
Dimension of working area in manufacturing machine	Dimensions of component	Section size + sequence	
	Shape	Dimensions of complete design	Dimensions of site
	Connection System	Shape	
Colour		Function	Activities in surrounding
Roughness	Appearance	Texture	Expression
	Opacity	Visual relationships	Views
Strengh	Resistance	Structural stability	Geological conditions
Acoustic transmission	Soundproofing	Sound level	Sound sources
	Openness	Ventilation	Wind direction
		Illumination (or Luminance)	Orientation
Conductivity	Insulation	Indoor temperature	Climate

Table 2. Parameters

Conclusions

This paper has described three projects of architectural arrangements with different components developed through the use of parametric design and digital manufacturing. The analysis of their properties reveals material and formal differences, but significant similarities in the organization of result, processes and products involved, comprising a structure of local, global, productive and environmental parameters where different aspects involved can be recognized. We also acknowledge that implemented parameters correspond to conditions related to manufacturing, connectivity, support, functionality and expressivity of the elements and the proposed form, presenting a repertoire of similar dimensions and variations as well as sets of initial products and final configurations, suggesting a specific field of exploration focusing on the kind of lightweight installations outlined. In this sense it would be relevant for further research to focus on aspects related to more complete conditions, such as structure, space and insulation.

The projects suggest the development of design systems based on some of these implemented parameters in various computing platforms defining open and variables processes, where the configurations developed appear as circumstantial possibilities. This suggests a particular kind of architectural research, aimed at defining general procedures, with control of specific elements and conditions, extracting specific solutions for specific situations, unlike the conventional process, which starts with a wide range of initial elements and combinations to execute specific works. Following this approach, buildings are set as combinations determined by the intensive application of technical aspects.

Acknowledgments

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Arturo Lyon is an architect who graduated from the Catholic University in Chile and Masterin Architecture from AA's Design Research Laboratory. After finishing his studies he worked at Zaha Hadid Architechts in London for two years focusing on the use of parametric design and algorithms for the resolution of doubled curved paneling systems as well as conceptual designs for different projects in China and Middle East. He has taught at the AA Landscape Urbanism Programme and workshops on Generative Algorithms and Parametric Design at the AA and at the Catholic University in Chile. He is currently Assistant Professor at the Catholic University in Chile and partner at LyonBosch architects.

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