This book is published in the scope of **Parametric Reciprocal Structures** workshop of design and fabrication, that took place at the Architecture School of Minho University and Guimarães Design Institute, July 5-25, 2016. The workshop was organized by Paulo J. S. Cruz & Bruno Figueiredo and promoted under the auspices of ICSA2016 it involved students of the Special Structures course from the MIARQ (EAUM), on the design and fabrication of mutual structure pavilion.

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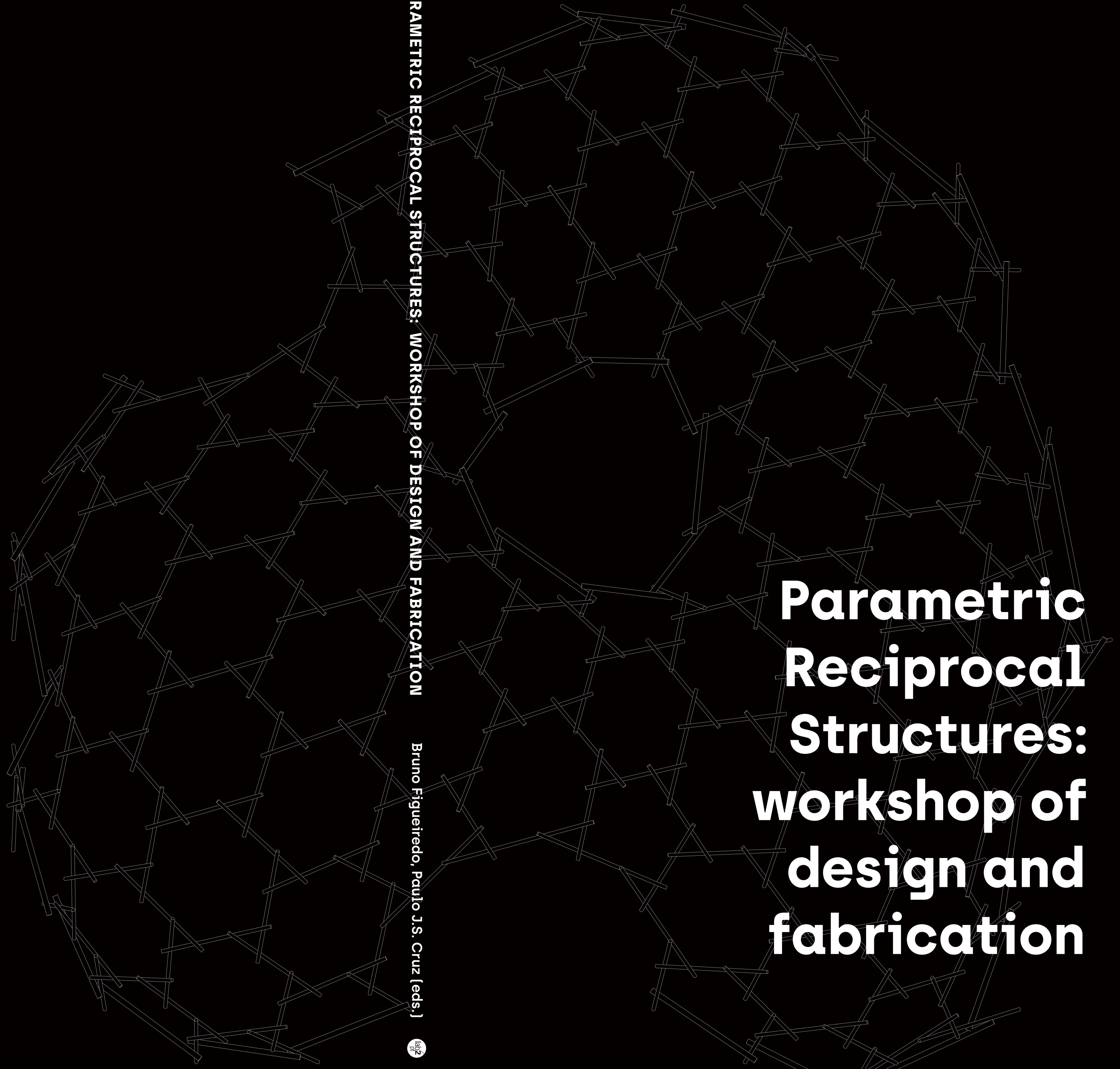
PARAMETRIC RECIPROCAL STRUCTURES: WORKSHOP OF DESIGN AND FABRICATION

Bruno Figueiredo, Paulo J.S. Cruz (eds.)



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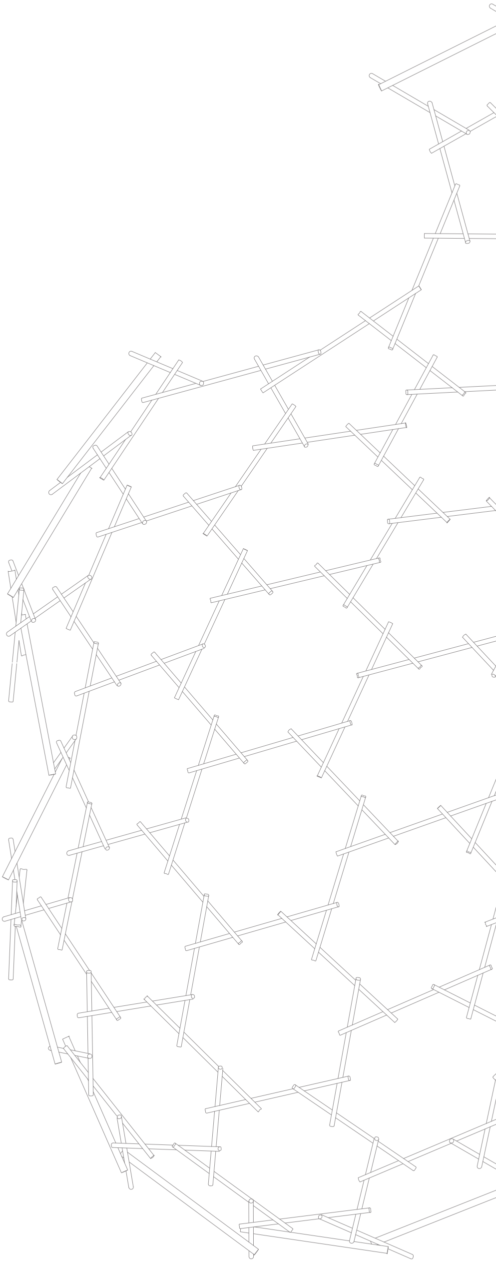

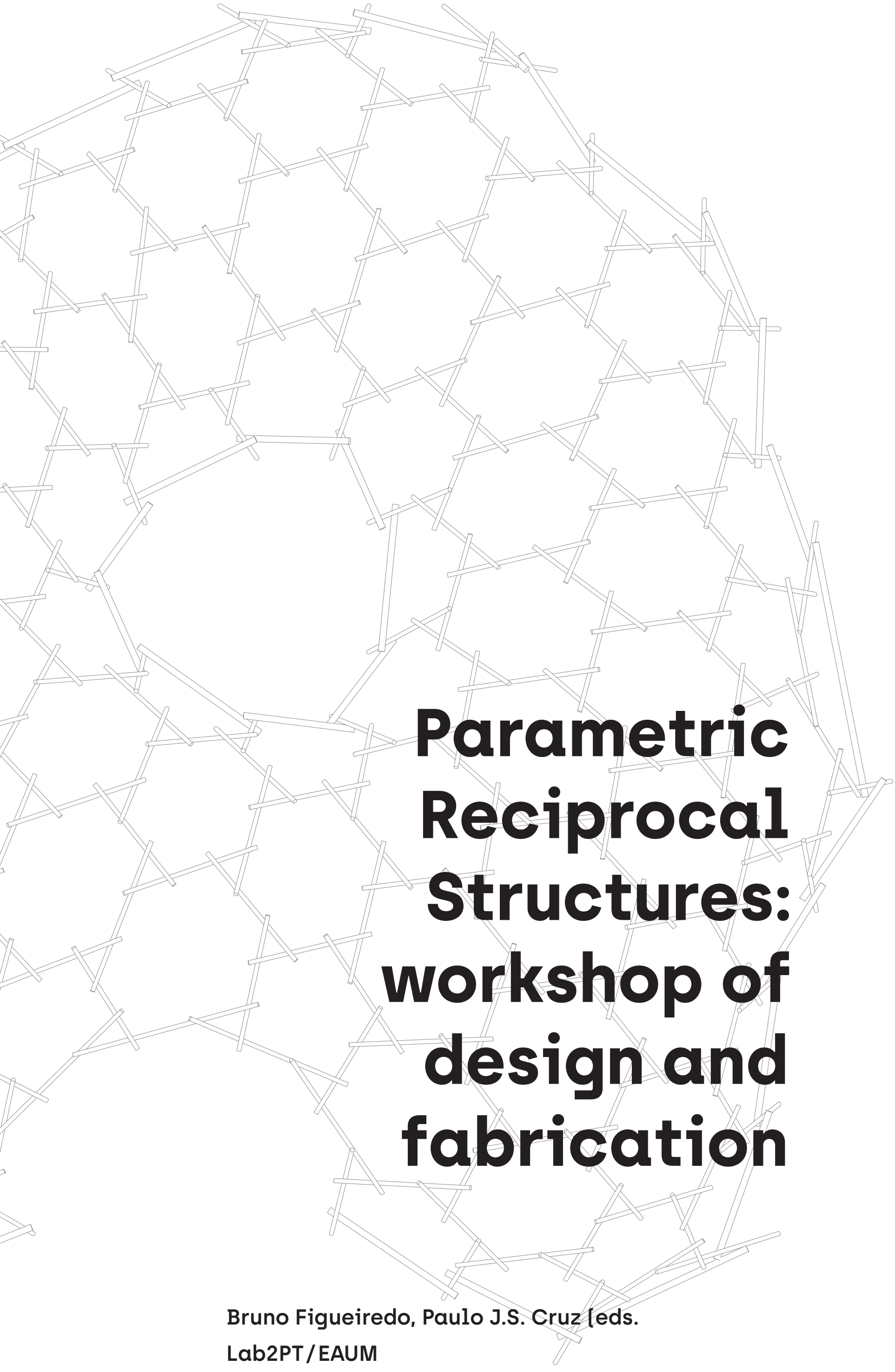

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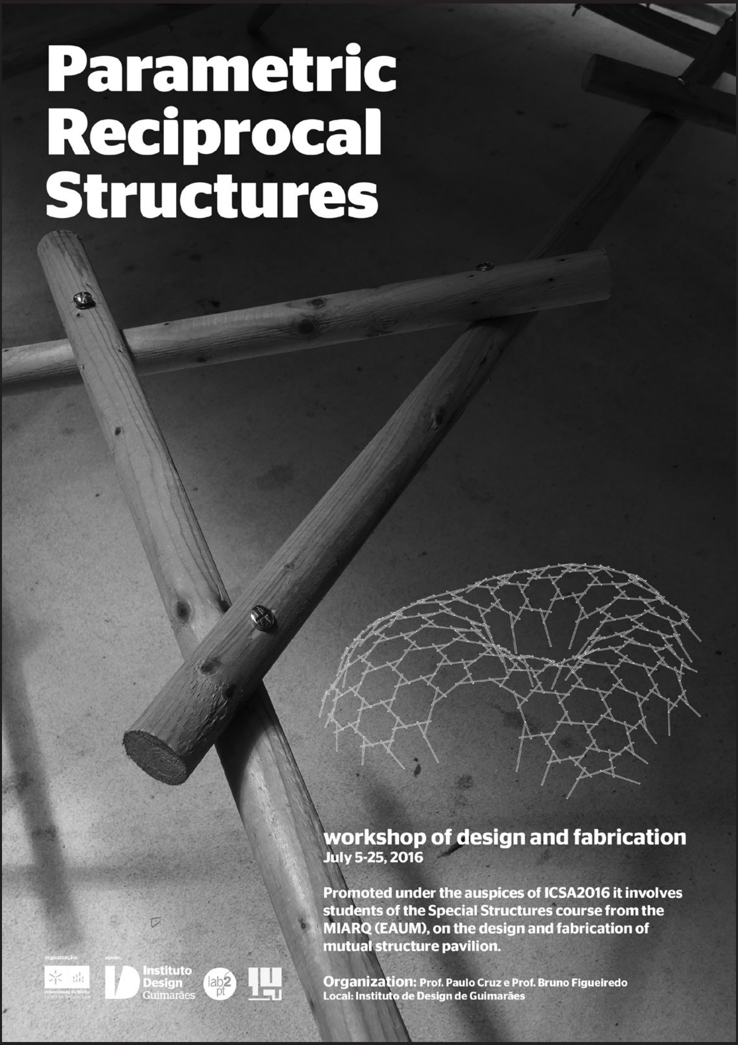

Parametric Reciprocal Structures

workshop of design and fabrication
July 5-25, 2016

Promoted under the auspices of ICSA2016 it involves students of the Special Structures course from the MIARQ (EAUM), on the design and fabrication of mutual structure pavilion.

Organization: Prof. Paulo Cruz e Prof. Bruno Figueiredo
Local: Instituto de Design de Guimarães

organização:
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FOREWORD

Paulo J. S. Cruz & Bruno Figueiredo

One of the central challenges that needs to be maintained throughout new structural and constructional design pedagogy is how to impart knowledge about structural and constructive concepts in a manner that enhances the capacity to understand and apply them in design.

Promoted under the auspices of the International Conference on Structures and Architecture — ICSA2016, the workshop "Parametric Reciprocal Structure: workshop of design and fabrication" had it genesis in proposals developed by students of the course of Special Structures of the Master in Architecture of the School of Architecture of the University of Minho (EAUM). The solutions designed by the students focused on the design of a reciprocal structure to be built at the Design Institute of Guimarães (former Tanning Factory of Ramada).

The reciprocal structures workshop was organized as part of the special structures course. The workshop involved students and staff to implement constructive solutions, in the manufacturing and in the assembling of the structure.

The initiative aimed to explore architectural and structural design concepts, embracing the research of: methods and processes of designing thinking; simulation and processing tools; and manufacturing concepts and materials.

The computational model Reciprocalizer, developed by Prof. Dario Parigi from the University of Aalborg, was used for the morphological design exploration. This model allows the generation of three-dimensional reciprocal grids, characterized by a high degree of freedom and formal experimentation.

The proposed combination of creative aspects in the conception and construction of structures, advanced technologies and complex architectural and structural applications represents a valuable learning experience of collaborative work.

RECIPROCAL STRUCTURES: THEIR IMPORTANCE TO THE PEDAGOGY OF STRUCTURES AND CONSTRUCTION IN AN ARCHITECTURE SCHOOL

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The meaningful changes in design and construction processes operated in the recent decades, make pertinent the weighting of some basic methodologies of the architectural practice. Effectively, several theoretical frameworks have changed, namely those associated to materiality, objects, assemblages and performance of structures and constructions (Nilsson, 2013).

Expanding tools for new pedagogical challenges

In the 1990's the emergence of computer aided software brought about the development of digital fabrication technologies. In our post-digital era, technological developments in materials, construction techniques and sustainable systems constitute the many advancements that call for new approaches to design (Olsen & Mac Namara, 2014).

The legacy of the essentialist approach to architecture precluded the productive and rich capacity of matter to define or influence geometry. Allowing this dynamic to operate is especially important not so much in the realm of new materials for architecture but as a way of conceiving tectonics and organization (Reiser & Umemoto, 2006).

By understanding the potential of the materials and of the respective construction methods used, and by transforming them into a design solution, which reflects the logic of the construction, the appearance of an architectural structure and the associated process of construction are united (Bech-Danielsen et al., 2012).

In the last decades tectonics has been brought forward in relation to a critique of modern production technologies (Nilsson, 20007) and holds the potential to become an active and progressive mean to further develop architecture based on technology and mass production.

Recently the European Commission published an action plan describing actions endorsed to accelerate the take-up of design in innovation policies at European, national and regional levels and to create the capacity and competencies needed to implement these policies. This document highlights the importance of the progressive shift in emphasis of European innovation policy from exclusive reliance on technology towards more demand and user-driven innovation (SWD, 2013).

The University has a profound obligation to not only prepare students for professional practice, but to instil values that define a trajectory and future for each disciplinary field. For Schools of Architecture that strive to impart creativity and technical skills to produce innovative design proposals, interdisciplinary workshops are necessary and crucial in the effort to achieve a more holistic understanding of the practice of architecture.

One of the central challenges that need to be maintained throughout new structural and constructional design pedagogy is how to impart knowledge about these concepts in a manner that enhances the capacity to understand and apply them in the design. One solution to promote visualisation is to engage students in haptic experiences to enhance their conceptual learning by using physical activity as a cognitive anchor to comprehend and apply abstract concepts in really situations (Vilquin, 2013). Haptic learning refers broadly to the importance of physical engagement to the educational process.

Physical models can be used in order to study the structural behaviour of an architectural project. Morphology and proportions are the components of structural design that can be easily apprehended – which are also the most important ones from an architectural point of view.

Therefore, framing of structural systems into uncommon architectural fields olds a great potential. In an experimental research framework, older experiences and case studies can be studied in new situations and renovated configurations (Vrouwe, 2013).

The term Haptic, which derives from the Greek "haptikos" or "able to touch", has been used since the early 1930's to describe the study of touch and, more broadly, how touch contributes to human interaction with the environment. Auditory and visual channels have traditionally made up the bulk of university education, but studies suggest that over one-third of our world-knowledge is obtained through some form of touch. Haptic 'channels' thus offer largely untapped opportunities for learning, particularly in classes that deal with physical properties (Dong, K. & Leslie, 2010).

Architectural education uses haptic learning almost by default in the reliance on models in design studios to explore and represent physical conditions. However, haptic methods have potential in technology courses as well, particularly those that deal with tangible physical properties and processes.

For a long time, craft and computation seemed total opposites. Where craft strongly resonated with the material world, computational architecture emulated an immaterial world of dots, lines, surfaces, scripts and algorithms. Since digital production techniques have become more accessible, the distinction between design generation and design production has decreased rapidly (Leach et al., 2004). Through digital fabrication, the traditional craft, precision and techniques, former practiced and trained during a great part of the craftsmen's existence, became available for computational architects directly (Bonwetsch et al., 2006).

Focusing on geometry, studio design and research exercises often do not prioritise the importance of material and techniques. In this context, technical aspects are considered as a neutral set of knowledge that is discussed briefly in later stages of the design process (Weinand, 2009). However, decisions in material and fabrication methods are no innocent choices. Integration of material and techniques correctly in earlier design phases often brings forward a more fluent process and a more cohesive result (Oxman, 2007).

The simultaneity of both material aspects and cultural dimensions is an important condition behind conceiving and constructing architecture. Frascari describes the concepts "constructing" and "construing" in his essay "The Tell-the-tail Detail" (Frascari, 1984). Constructing relates to the physical act of building, of assembling building elements, while construing is about creating meaning.

Today, with the advent of digital media technologies and the ability to conceptualise, express and produce complex forms using digital means, the question of the status of the architectural form is once again under consideration. Indeed, the questions concerning the method of form expression in contemporary architecture, and its meaning, remains very much open (Grobman, Y.J & Neuman, 2011).

Vrouwe & Pak (2013) explored "framing" and "frame experimentation" as a potential method or approach in teaching to accompany this change in learning. In this light, framing is used as conceptual scaffolding. This scaffolding has already been used in a different context to organise experiences and guide the trial-and-error approach to meaningful tacit knowledge (Benford & Snow, 2000).

Frame experimentation is often used to rethink or reconnect conventions in multidisciplinary social sciences (Goffman, 1974). However, the use of these conceptual reframing strategies in design based studies is less frequent. Therefore, framing of architectural systems into uncommon fields holds great potential. By using frame experimentation, older experiences can be studied in new situations; tacit unconscious knowledge can become more tactile in action Vrouwe & Pak (2013).

Bundgaard (2013) proposes the concept of ‘montage’ as a means for investigating possible strategies and as a generator for creating architecture, which on an industrial basis responds to sustainability, and at the same time reflects the heterogeneity, individualisation and need for adaptation that characterises today’s society. As an approach, montage generates alternative contexts. Potentially, current principles and premises allow an opportunity for architectural experimentation and for developing new formal idioms, architectural hierarchies and expressions.

Tensegrity structures, in addition to their uncommon structural basis and appearance, are characterised by almost no separation between architectural expression and structural configuration. Accordingly their spatial and tectonic organisation that derives from their structural configuration also determines their aesthetic and functional features (Liapi, 2013).

The structural principle of mutually supporting beams in a closed circuit was used in the past in vernacular buildings and in studies by Renaissance architects in the form of 2D and 3D grillages (Thönnissen, 2013). In 1987 the designer Graham Brown rediscovered the structural principle and its potential in architecture, renaming it the Reciprocal Frame (Brown, 1989). Other terms used to describe this kind of spatial structures are: lever-beam structures (Bertin & Hebelstabwerke, 2001); mutually supported element systems (Rizzuto, 2007) and nexorades (Baverel, 2000).

Structures based on the principle of reciprocity have been autonomously studied and used since the antiquity on the basis of different needs and purposes. The application of the principle of reciprocity requires the presence of at least two elements, at the same time both supporting and being supported by the other with no hierarchy, meeting along their span and never in their vertices. Neolithic structures and known Indian tipis may be examples of this. However, the first known written reference to a structure that can be considered reciprocal comes from Japan when, in the twelfth century, Buddhist monk Chogen (1121-1206) described a technique of overlapping spiral wooden beams, which was used in the construction of temples.

Inspired on folio 899v of the Leonardo *Codex Atlanticus*, in 1989 Rinus Roelofs, a Dutch mathematician and architect, began constructing domes using notched bars assembled according to a simple rule. This led him to explore planar constructions based on this rule using fixed length "notched" linear segments, creating a wide variety of patterns (Roelofs, 2008). Since 1995 he actively promoted a significant number of dome construction projects, exhibitions and workshops in Belgium, Germany, Hungary, Italy, Portugal, Serbia, Slovenia, Spain, Taiwan and the Netherlands (http://www.rinusroelofs.nl/structure/structure-00.html).

Amateur architecture studio was founded in 1998 in Hangzhou, China, by two of the most outstanding architects of China. In 2012 Wang Shu was recipient of the Pritzker Prize, recognising "the exceptional nature and quality of his executed work, and also for his ongoing commitment to pursuing an uncompromising, responsible architecture arising from a sense of specific culture and place". By using recycled materials, they are able to send several messages on the careful use of resources and respect for tradition and context as well as give a frank appraisal of technology and the quality of construction today. The "decay of a dome" reciprocal structure they built in the 2010 Architecture Venice Biennale 2010 is clearly rooted in the architecture's origins and Chinese tradition.

Reciprocal structures were first originated as assemblies of elongated elements. This typology is low-cost and relatively simple in fabrication, enabling the possibility to generate complex free-form shapes with standard elements and simple jointing techniques; conversely, it requires engaging in a complex non-linear, non-hierarchical, iterative design process. Their geometry cannot be described with hierarchical, associative parametric modelling. Instead the geometry of the network is a property emerging, bottom-up, from the complex and simultaneous interaction among all the elements in the network.

The reciprocal systems are usually based on a periodic mesh, consisting of a set of regular or irregular polygons (triangular, quadrangular, pentagonal, etc.). More complex and non-periodic compositions result from the combination of different types of polygons (such as those based on Penrose-like patterns). In the first case, the number of bars that converge for knots is uniform throughout the mesh. In the second, the number of bars that are associated in each node may be variable.

The main challenge of the pedagogy of structures and construction in an architecture school lies in the process of transmitting the basic concepts in a way that involves the students in the learning process and that improves the students' ability to assimilate and apply that knowledge in the design. For that reason reciprocal structures arouse a growing interest because they constitute an experimental field to combine tools of parametric drawing and digital manufacturing, with simple structural concepts and materials, to obtain complex and appealing geometries.

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ADVANCES IN FREE-FORM RECIPROCAL STRUCTURES: COMPUTATIONAL TOOLS FOR DESIGN AND FABRICATION

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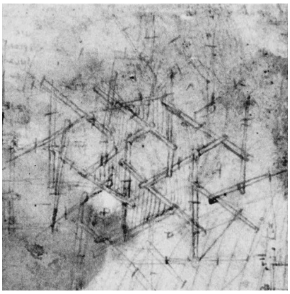
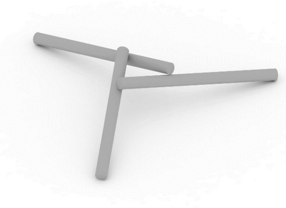
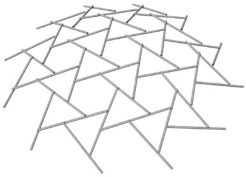
The principle of reciprocity has been known since antiquity, and albeit its application in structures as old as the first domes, slabs and bridges, its presence in the built world has been somehow limited and sparse. An early investigation of these structures worth mentioning is the work Folio 899 of the *Codex Atlanticus* (figure 1) by Leonardo Da Vinci. More recently reciprocal structures have sparked a renewed interest among professionals and researchers due to the unique design opportunities that they offer when combined with the use of computational form finding tools. From a didactic standpoint, they challenge the traditional sequence of form definition, structural dimensioning and detailing, as the shape cannot be defined a priori, rather is the result of continuous and iterative negotiations between the designer's intention, the detailing and the structural dimensioning.

The Reciprocalizer is a plug-in for Grasshopper — the parametric interface for McNeel´s Rhinoceros 3D — developed by the author to solve in real-time the geometry of reciprocal structures based on parameters controlling the way bars meet in each joint. In doing so, it effectively embeds the tectonic of construction within the geometrical solver, and renders the constructive detail an active element in the design process. It was developed within the Performance Aided/Assisted Design (PAD) framework, applied within







1. Extract from the fol. 899v of the *Codex Atlanticus* by Leonardo da Vinci

2. A simple three-bars reciprocal configuration with superimposition joint

3. A 3D visualization of Leonardo’s sketch of figure 1 the context of the master programme in Architecture and Design at Aalborg University. It aimed to investigate the potential of integrating considerations on material, detailing, and construction in the early stages of the design process. The Reciprocalizer is a paradigmatic example of the "embedded tectonics" factor in the PAD framework because in reciprocal structures the constructional aspects cannot be detached from the geometry, and the joint specification determines the global geometry of the configuration.

THREE DIMENSIONALITY IN RECIPROCAL STRUCTURES

In their purest form reciprocal structures are characterised by a simple, almost elementary, and yet remarkable connective system, which allows for a load-bearing structure to be created by interlocking through juxtaposition any three straight standard bars. The elements arranged with this technique – a superimposition joint - would stand stiff and be able to hold a load through pure friction without the need of any additional jointing element (figure 2).

The natural out-of-plane development of reciprocal structures based on superimposition joints is a well known morphological aspect caused by un-notched bars sitting on the top, or in the bottom, of each other [1]. An example can be drawn from Leonardo da Vinci's reciprocal arrangement shown in figure 1. Despite not being evident from his representation, once elements are placed on top of each other (figure 3), they naturally develop into an out-of-plane, dome-like structure.

The extent of the out-of-plane deviation varies depending on a set of parameters that describe the superimposition joint at any connection: the eccentricity, the engagement length, and the top/bottom position. The effect that any of the parameter values entails on the overall geometry can be used to generate a potentially infinite variety of new geometries by employing the same set of standardised elements. This can be observed already in a three bars configuration (figure 4, 5).

0.8 0.5 0.3 0.2 0.1

0.05 0.1 0.18 0.26 0.34

4. The effect of the engagement length on the out-of plane deviation

5. The effect of the eccentricity on the out-of plane deviation

The eccentricity value, in the case of a superimposition joint, is directly dependent on the elements thickness and shape. However the value can be changed if a different type of connection is sought (axial connection), or can be increase/decreased if the distance of the elements axis is modified with the use of notches or additional joint spacers.

SIMPLICITY *VS.* COMPLEXITY IN CONSTRUCTION AND DESIGN

The fundamental simplicity of a reciprocal structure joint applies to both small and large irregular configurations. The presence of always two and no more than two bars in any connection, and regardless of the complexity of the configuration, allows to engineer simple, adaptable connections in full scale real-world projects.

On the other hand, the intrinsic three dimensionality of reciprocal structures emerges as one of the most interesting but at the same time complex feature of this typology. The out-of-plane deviation cannot be determined directly with standard CAD or parametric tools. In fact the intrinsic three-dimensionality of reciprocal structures cannot be separated by the non-hierarchical nature of the principle of reciprocity. Due to the non-hierarchical nature, the position of the elements at each joint influences the spatial position of each and every other element in the configuration. The resulting geometry cannot be predicted in a straightforward manner and can only be understood as a characteristic that emerges from the complex interaction between all the elements: shape, topology and position [3]. In order to design a reciprocal structure the geometric compatibility must be achieved simultaneously for all bars, since the re-adjustment of one bar's position would affect the geometric compatibility of the adjacent elements that in turn should be adjusted and propagated to the rest of the configuration.

THE RECIPROCALIZER

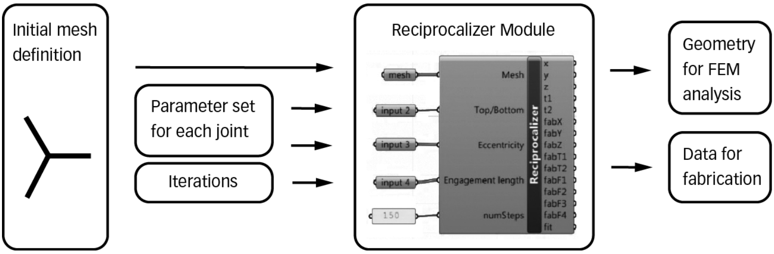
The three-dimensionality and non-hierarchy renders the design of a reciprocal structure particularly complex. However, when approached with the use of computational tools, it can be considered a design opportunity. With the use of straight bars and superimposition joints any kind of geometry can be generated.

The Reciprocalizer is a module that embeds the complex, iterative and non-hierarchical tectonic of reciprocal structures, and therefore allows predicting and controlling the design and geometry of large networks of reciprocally connected elements. In a typology where complexity is shifted from manufacturing to design, the Reciprocalizer module allows to engage in the design of reciprocal structures, at the same time that it enables the creation of an infinite variety of complex three-dimensional structures, while employing standardised wood components.

The Reciprocalizer can handle the three-dimensionality of reciprocal structures by iteratively finding the geometric compatibility of elements: the unknown is the geometry, and the given data are the values of the geometric parameters (Figure 6). It embodies one of the most interesting features of reciprocal structures, i.e. the ability to generate the geometry bottom-up from the assembling parameters values set at the joints. It therefore allows to interactively explore the influence, often unpredictable, of the joint parameters values on the overall geometry, therefore triggering the exploration of the geometrical richness of reciprocal structures and the emergence of original designs through the modification of the Reciprocalizer inputs: the initial mesh topology, and the fundamental joints parameters.

GEOMETRIC PARAMETERS

The geometry of a reciprocal structure depends on the topology of the initial mesh, on the fixed end points, and the set of fundamental parameters at each superimposition

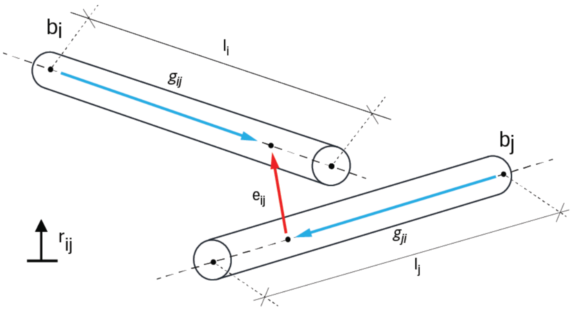


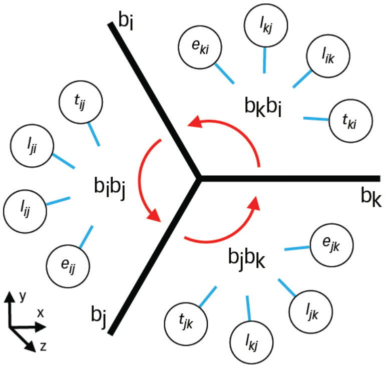
6. Schematics of the Reciprocalizer inputs and outputs

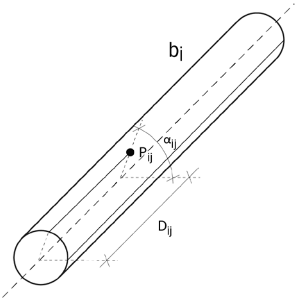
joint. For a connection between two elements b_i and b_j the parameters are computed:
– the eccentricity e_{ij}, that measure the distance between elements axes;
– the engagement ratio $l_{ij} = g_{ji} / l_j$, that measures the position in which elements bi meets element bj along its span;
– the engagement ratio $l_{ij} = g_{ij} / l_i$, that measures the position in which elements b_j meets element b_i along its span
– the specification of whether element b_i sits on the top or on the bottom of element b_j with respect to a reference vector r_j whose tip indicates the top position $t_{ij} = \hat{e}_{ij} \cdot \hat{r}_{ij}$ (figure 7).

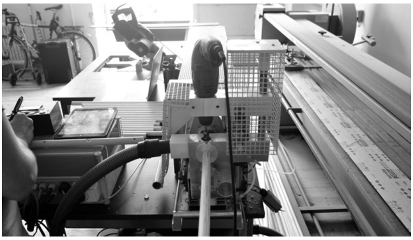
Connection Topology	p1	p2	p3	p4
b_ib_j	e_{ij}	l_{ij}	l_{ji}	t_{ij}
b_jb_k	e_{jk}	l_{jk}	l_{kj}	t_{jk}
b_kb_i	e_{ki}	l_{kj}	l_{ik}	t_{ki}

For a three-bar reciprocal configuration a total of 12 parameters are needed (figure 8, table 1). After computing the parameters values the solver generates an overall configuration while shifting the elements position accordingly. Due to the









7. The computation of the geometric parameters at each iteration and connection

8. The 12 parameters involved in a three-bar fan

9. The measure of distance and angle for each bar

10. The Reciprocalizer Robot

no-hierarchical nature of the configuration, the process must be iterative and will stop when a tolerance value or the maximum iterations number is reached. The calculation depth input allows definition of the number of iterations in the calculations and, therefore, allows a choice between faster and less precise solutions or slower and more precise solutions.

RECIPROCALIZER OUTPUTS

The Reciprocalizer module outputs the data for Finite Element Method (FEM) analysis and for the fabrication. The output for FEM analysis takes into consideration the need to introduce an additional element at each joint with a fictitious high stiffness that connects the elements axis of the elements.

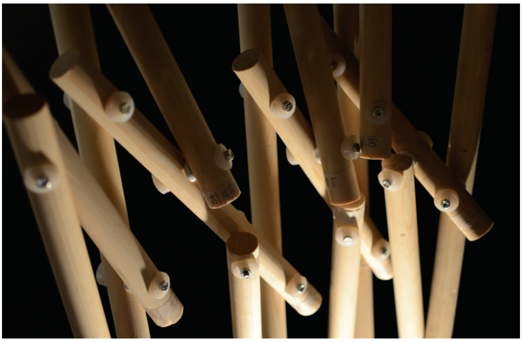
The output for fabrication consists on the data needed to identify, for each bar b_i, the point P_{ij} in which it meets the connected bar b_j. Each point P_{ij} is located along the element b_i surface and its position can be described with two values: the distance D_{ij} from the bar start point, and the angle α_{ij} that it creates with a reference origin line arbitrarily set on the side element, measured from the element axes and in a perpendicular plane (figure 9).

RECIPROCALIZER ROBOT

Because the whole geometry is the result of the local interaction between bars, precision at the joint level is crucial in order to obtain the goal geometry and to maintain the geometric compatibility during the construction process. The Reciprocalizer Robot was designed in order to transfer the necessary information from the digital model to the wooden bars (figure 10).

APPLICATIONS: PAD WORKSHOP SERIES 2012-2015

The Reciprocalizer has been used in a workshop series coordinated by the author from 2012 to 2015 for the Master of



11. The structure realized in the reciprocal structure workshop, fall 2013

12. The joint detailing

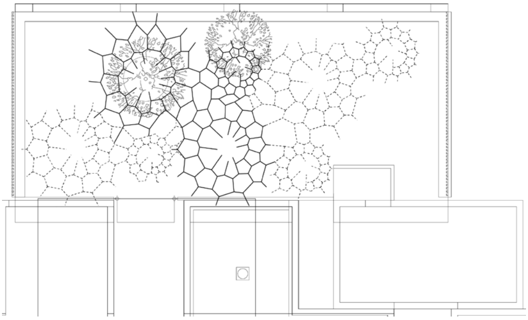
Science in Architecture and Design at Aalborg University, as part of the course “Performance-Aided Design: form, material, structure acoustic and fabrication”. The PAD workshop enabled the students with a hands-on experience on the changing relationship between form, structural behaviour, detailing and construction in a digital design environment. Each of the one week long workshops explored the design and fabrication processes of a reciprocal structure. This typology was chosen because it required dealing with the geometry, the structural dimensioning, and the detailing all at once and from the initial design stages. It was also considered to be an ideal typology to investigate an innovative approach to design and construction in a digital design environment.

Each year the workshop incorporated the latest findings and developments of the research program carried on Reciprocal structures by the author at the department of Civil Engineering at Aalborg University. The outcome of the workshop in turn stimulated further development in critical areas of the design process from conception to production.

The design brief since 2013 is the development of a roof for the cafe terrace in Have i Hune, a flower garden started in 1991 by the artist Anne Just and the architect Claus Bonderup in Hune. The roof should integrate with the elegant and balanced composition of both architectural and natural elements of the Have, including the trees growing from the terrace.

A small structure has been realised in 2013 for a preliminary testing of the digital design and manufacturing tools. The prototype is constituted by three connected tree-like columns, each one based on Fibonacci spirals, often found within flowers, embracing one of the existing trees. The pavilion constitutes the first application of the Reciprocalizer robot (figure 11,12 and 13) [3].

In 2014 an additional requirement was to include design explorations aimed at improving the structural behaviour. Those could be achieved by variations on the initial mesh density, on the number and length of elements and on the



dmax = 1.2cm   dmax = 0.63cm   dmax =0.045 cm

13. The initial mesh (the thicker lines have correspondance to the realzied part of the structure)

14. Effect of engagement length on the structural stiffness

15. The reciprocal structure realized in 2014 reciprocal structure geometric parameters: engagement, eccentricity and top/bottom position (figure 15). The aim was to achieve a balance between the requirements posed by the spatial, constructional and structural issues. Improved efficiency in the construction process allowed building a larger structure (figure 14).

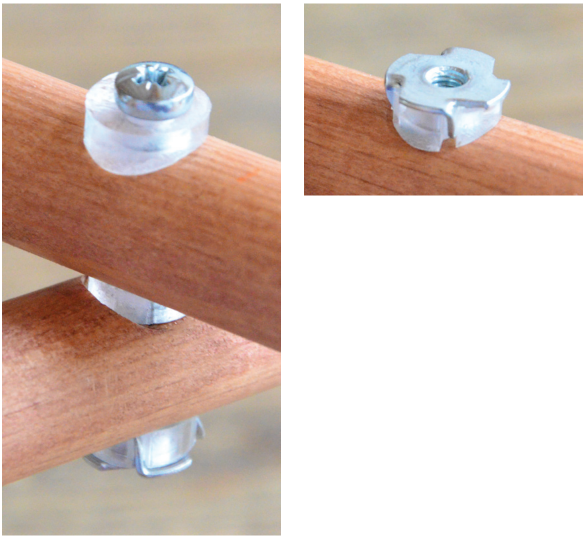
In 2015 different bars size were introduced to optimise the structural performance. Three timber member size - 22mmØ, 33mmØ and 43mmØ were assigned to the elements according to the utilisation ratio under load condition. Additionally the Reciprocalizer could now have an unlimited number of converging bars in a single node, enabling the possibility to generate and design an infinitely large set of reciprocal structures patterns.

LIMITATIONS AND ADVANTAGES

The design process experimented in the workshops challenged the traditional sequence of form definition, structural dimensioning and construction and it became a paradigmatic experience on fabrication-aware design. The designer has no direct control on the shape - instead it has control on a series of parameters related to structural dimensioning and construction / joint detailing that in turn generate the shape.

On the one hand, since the shape is not designed directly, the adjustment of the parameters to fit a specific design requirement might require several attempts and back and forth action. Especially with large configurations, the speed of the solver is not fast enough to allow a real-time manipulation of the shape, rendering fine adjustments more difficult to achieve.

On the other hand the designer must accept becoming part of an iterative process where form rather than imposed is gradually discovered, as a result of several negotiations undertaken at the interplay of the mesh and joint definition, plus structural analysis. Through this process, the shape driven by a construction detail that allows for a short time assemblage of the whole the structure based on a uniform adaptable



16. Drone´s eye view of the pavilion in Have i Hune, 2015

17. Joint detail

joint, allows for a new creative input from the part of the designer. Furthermore, as a by-product, this process triggers a novel exploration of the geometry of reciprocal structures, and the emergence of original, unexpected shapes.

CONCLUSIONS

The advances in design and fabrication of free-form Reciprocal Structures were presented, together with their application during several one-week long workshops held with the students of the 1st semester of the Master of Science in Architecture and Design, from 2012 to 2015, at Aalborg University.

Triggered by the use of the Reciprocalizer, the design process of reciprocal structures requires engaging in iterative processes between global shape, mesh definition and detail development. Such a design process challenges the traditional sequence of form definition- structural dimensioning and construction, as the shape is the result of continuous negotiations between a variety of geometric parameters, structural performance and intended spatial effects.

This design experience becomes almost paradigmatic for exemplifying the PAD framework, towards a “poetic of performance”, a design approach that explores the complexity intrinsic in the design process, and uses that complexity as a source of inspiration for creative work in architectural design.

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PARAMETRIC RECIPROCAL STRUCTURES: WORKSHOP OF DESIGN & FABRICATION

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One of the main pedagogical challenges in teaching structures and construction in an architecture school lies in the process of transmitting concepts in a way that engages the students in learning proceedings while promoting their ability to assimilate and apply knowledge in the design process.

For this to happen it is essential to provide them with the capacity to combine and synthesize concepts of architectural and structural design, comprising knowledge on design thinking methods and processes, simulation models and parametric design tools, as well as concepts and materials of manufacture.

This text presents a parametric reciprocal structure built in Guimarães in the Summer of 2016, during the workshop "Reciprocal Parametric Structures — Project and Manufacturing", held under the auspices of ICSA2016, the Third International Conference on Structures and Architecture. The workshop took place under the scope of the Special Structures course of the Master in Architecture of the School of Architecture of the University of Minho, coordinated by Prof. Paulo Cruz.

The workshop was held in two moments. In the initial phase, concepts inherent to reciprocal structures and the use of computational models were exposed and explored, followed by the development of design project proposals.

The second phase involved the selection of a design project to be developed and built. At this stage, and after design refinements, the students defined all the structural components, as well as the manufacture and assembly process of a real scale wood structure.

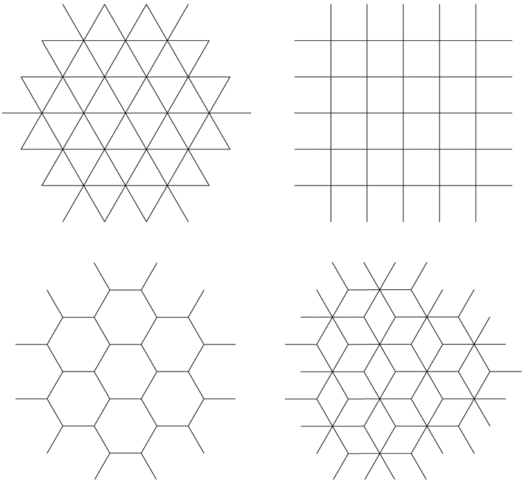
SIMPLE PARAMETRIC RULES FOR THE GENERATION OF FREE-FORM STRUCTURES

Proposed by Graham Brown in the 1980's, the term "reciprocal structures" refers to structural systems of self-supported elements in a closed circuit in which, from the delicate interaction and dependence of these elements, stable structures are achieved.

Similar concepts can be found in many ancestral constructions. Some Neolithic structures and the well-known Indian tepees can be examples of this. However, the first known written reference to a structure that can be considered reciprocal comes from Japan when, in the 12th century, the Buddhist monk Chogen described a technique of superimposing wooden beams in spiral relation, which was used in construction of temples [1]. Also relevant are the studies developed by Leonardo da Vinci in the 15th century where he explores such geometries.

Reciprocal systems are usually based on a periodic mesh, being constituted by a set of regular or irregular polygons (triangular, quadrangular, pentagonal, etc.). More complex and non-periodic compositions result from the combination of different types of polygons (such as those based on Penrose-type patterns). In the first case, the number of bars that converge in the knots is uniform throughout the entire mesh. In the second, the number of bars that are associated in each node can be variable (figure 1).

The workshop began with the exploration of mechanisms for the operation of reciprocal structures. The approach taken also considered the fact of the participants being students of architecture, without deep knowledge of the calculations

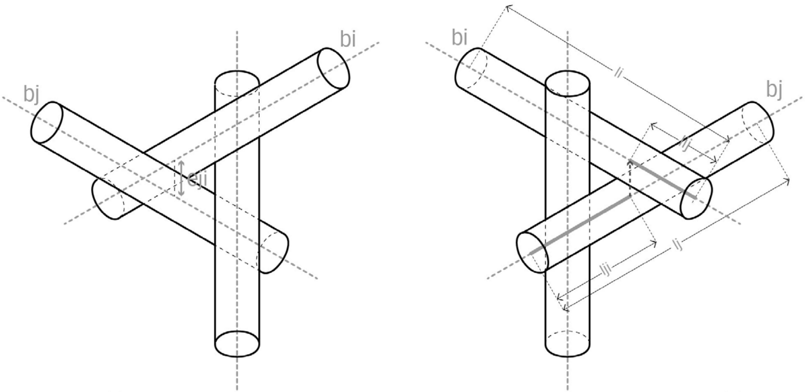


1. Patterns for the definition of reciprocal structures

inherent to this typology of structures. The possibility of designing and constructing large-scale structures, besides providing the students with haptic feedback, allowed to acquire a better grasp of the different types of three-dimensional spatial meshes and the main parameters that define them.

Most importantly it was essential that the students honed the design of their initial mesh and ably controlled the parameters that constrained the junction knots between bars in order to generate their three-dimensional structures.

As shown in figure 2, the union by superposition of two bars (b_i and b_j) is conditioned by: the eccentricity of the bars (e_{ij}), the distance in which the bars are supported (l_{ij}), the positional relationship of the bars, in a sequence up-down or down-up, and the sense of arrangement of the bars in the nodes, being able to adopt the clockwise or anti-clockwise direction.



excentricity (e)

direction: clock wise
position: bottom-up

connection ratio (lji)

direction: counter-clock wise
position: up-down

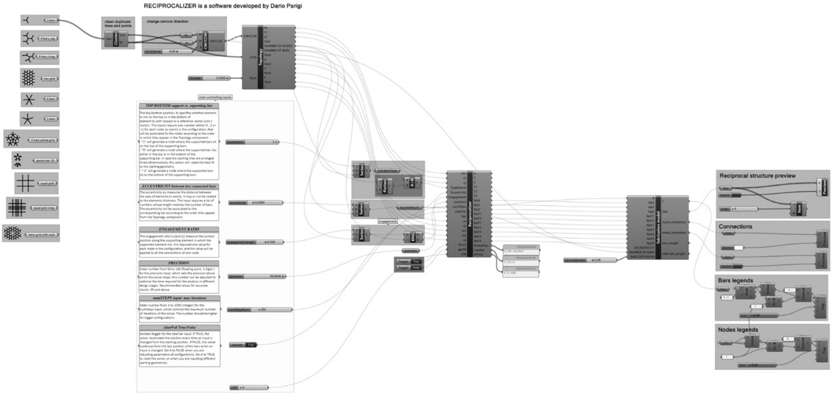
2. Parameters for the definition of a union node of reciprocal geometries

Although is possible to synthesize reciprocal structures behaviour in very few parametric rules, the geometrical pattern and solutions that can be achieved are endless.

In recent years several researchers developed different form-finding computational models with the aim of exploring and automating the generation of this type of structures. Baverel et al. (2004) proposed the use of genetic algorithm to configure nexorades or multireciprocal structures [3]. More recently, Alan Song-Ching Tai (2012) also recurred to genetic algorithm and graph searching algorithms to find optimized notching configurations that guarantee an assembly sequence [4]. Within the framework of Grasshopper®, Daniel Piker developed Kangaroo — a live physics engine for the simulation, form-finding, optimization and constraint solver — that lets to implement a set of interactive computational methods for the simulation of structures under valid force equilibrium, allowing to test the generation of reciprocal structures from an initial mesh [5]. Or the researches of Udo Thönnissen [6] at ETH in Zurich and Dario Parigi et al. [7-8] at Aalborg University and by the development of computational models for the morphogenesis of reciprocal structures.

PARAMETRIC MODELLING WORK-FLOW

The computational model Reciprocalizer was used for the exploration of different morphological possibilities achievable with reciprocal structures. Developed by Dario Parigi, Reciprocalizer is implemented in Grasshopper®. Its programming paradigm allows the visual development of parametric models whose result corresponds to a wide universe of solutions (figure 3). As aforementioned in the previous chapter, departing from the definition of an initial mesh, the Reciprocalizer allows: to generate interactively three-dimensional reciprocal grids, characterized by a high degree of freedom and formal experimentation; to define the geometric pattern of the mesh, y easily adapting to context constrains; to the design of the components of the structure.



RECIPROCALIZER is a software developed by Dario Parigi

TOP/BOTTOM support vs. supporting bar

The top/bottom position, tij specifies whether element bi sits on the top or in the bottom of element bj with respect to a reference vector (unit z vector). The inputs require one number (either 0, 1 or -1) for each node (or point) in the configuration, that will be associated to the nodes according to the order in which they appear in the Topology component.
- "1" will generate a node where the supported bars sit on the top of the supporting bars.
- "0" will generate a node where the supported bar sits either in the top or in the bottom of the supporting bar. In case the starting lines are arranged three-dimensionally, this option will reate the best fit to the starting geometry.
- "-1" will generate a node where the supported bars sit on the bottom of the supporting bars.

ECCENTRICITY between two connected bars

The eccentricity eij measures the distance between the axes of elements bi and bj. It may or not be related to the elements thickness. The input requires a list of numbers whose length matches the number of bars. The eccentricity will be associated to the corresponding bar according to the order they appear from the Topology component.

ENGAGEMENT RATIO

The engagement ratio lij (and lji) measure the contact position along the supporting element in which the supported element sits. It is required one value for each node in the configuration, and the value will be applied to all the connections of one node.

PRECISION

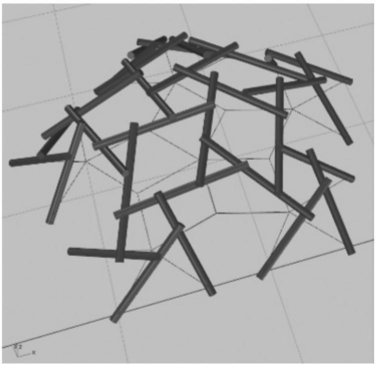
Slider number from 50 to 100 (floating point, 3 digits) for the precision input, which sets the precision above which the solver stops: this number can be adjusted to optimize the time required for the analysis in different design stages. Recommended values for accurate results: 99 and above.

numSTEPS input: max iterations

Slider number from 1 to 1000 (integer) for the numSteps input, which controls the maximum number of iterations of the solver. The number should be higher for bigger configurations.

clearVal True/False

boolean toggle for the clearVar input. If TRUE, the solver recalculate the solution every time an input is changed from the starting position. If FALSE, the solver continues from the last position of the bars when an input is changed. Set it to FALSE when you are Adjusting parameters of configurations. Set it to TRUE to reset the solver, or when you are inputting different starting geometries.



3. Rhinoceros Graphical interface and Grasshopper using Reciprocalizer. Simulation of the generation of a reciprocal structure based on a Penrose mesh

In addition to the presentation of basic concepts related to reciprocal structures, the workshop focused on specific aspects of this type of structure and on the use of visual programming languages dedicated to design generative systems. Subsequently, and starting from the hypothesis of using parametric computational models, the principles for the derivation of this type of structures were presented through the Reciprocalizer. This process was undertaken in two stages.

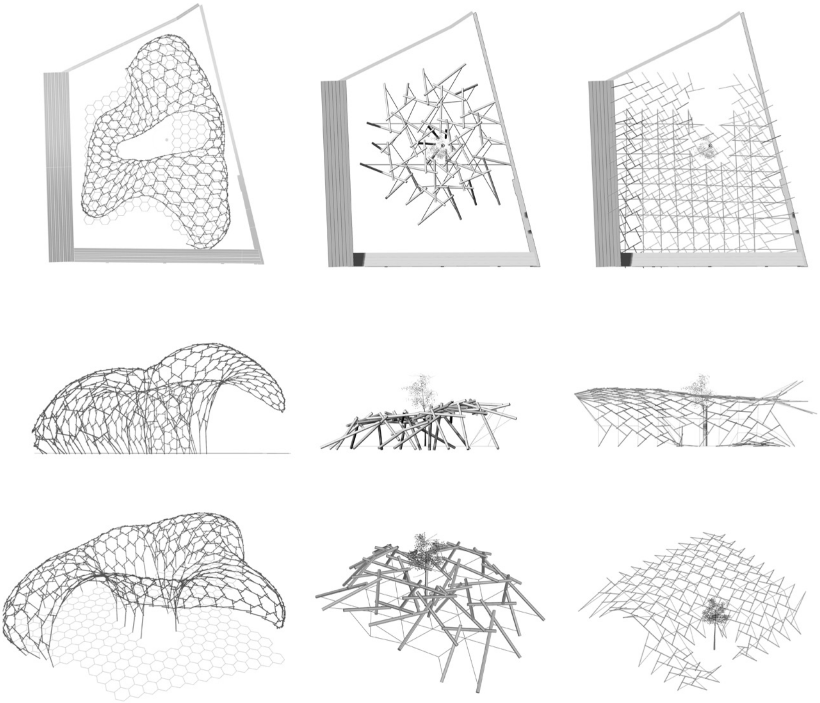
The first stage, prior to the generation of the reciprocal structure, consists in the definition of a set of geometric meshes, varying between regular and irregular polygonal patterns. Its objective is to regulate the overall composition of the structure, to establish the quantity of linear elements (bars), their relative positioning and that of the joint knots. Figure 1 shows some of the possible geometric meshes defined, varying between triangular, quadrangular, hexagonal and Penrose patterns.

In the second stage, different design solutions were explored, based on previously defined meshes. The geometry results from the manipulation of parameters related to the definition of knots and bars. Any variation of the parameters presented in figure 2 — eccentricity, engagement ratio and the direction and order of positioning of the linear elements — affects the configuration of the overall structure, resulting in more or less convex structure segments.

PARAMETRIC RECIPROCAL STRUCTURES WORKSHOP SYLLABUS

Once introduced the basic concepts inherent to the use of parametric models and the generative principles underlying the Reciprocalizer, students were asked to develop proposals for a reciprocal structure that would be built in the courtyard of the Design Institute of Guimarães (IDEGUI).

The syllabus asked each working group to define a design project strategy that took into consideration the location, the morphology of the spatial structural mesh and its feasibility.



4. Proposals presented by the students for reciprocal structures based on three geometries: hexagonal (left), Penrose (center), quadrangular (right)

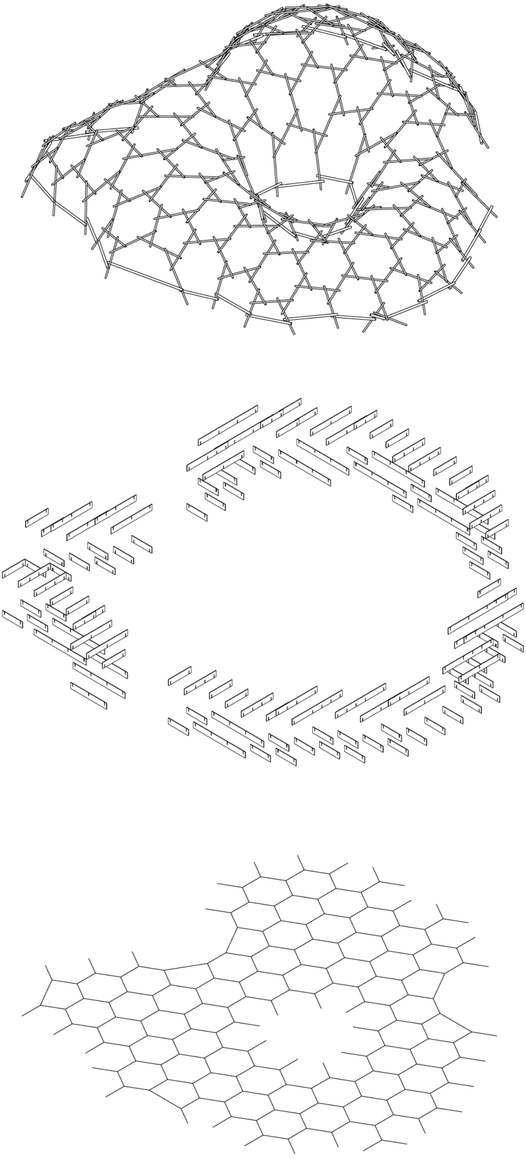
In order to explore the morphological potential of the reciprocal structures, each group was in charge of exploring the derivation of proposals according to a specific type of geometric pattern — varying between triangular, quadrangular, hexagonal and Penrose meshes. In addition to the geometric composition of the grid, its density and volume. The enunciate also requested an analysis of the diversity of solutions that would be obtained through the variation of the values attributed to the different parameters underlying the generation of the general structure.

DESIGN PROPOSALS

The universe of solutions proposed by the students show the variety of approaches and the flexibility that this type of structure allows for. Figure 4 illustrate some of those proposals.

The structure made from an hexagonal mesh consists of a large-scale structure that practically occupied the entire IDEGUI courtyard. The morphology of the structure is characterized by a curvilinear perimeter, with empty areas on the northwest and southwest in order to mark the entry points of the inner space of the structure. The majority of the anchoring points are located in the central space of the patio, surrounding an existing small tree, liberating altimetricaly a large part of the structural grid, resulting in a surface with a shape similar to a mushroom cap.

The proposal derived from the Penrose mesh is defined by a concentric movement with a circular perimeter and a central void space where the tree is located. The volume also aims to create an internal circulation around that void. The structure is supported along its outer perimeter, both on the ground and on the south-west limit wall of the courtyard. Contrary to what happened in the previous strategy, the alternation of the Penrose mesh, between quadrangular and triangular polygons, results in knots with three and five joints, forming a more complex structural scheme than the previous solution. Although there was a large number of



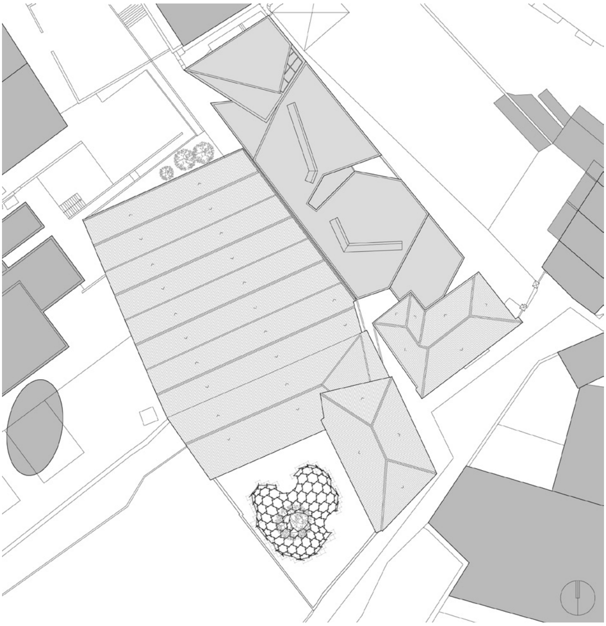
5. Axonometric view from the (a) initial mesh, (b) the foundations parts and (c) the spatial structure bars in the hexagonal structure with a relatively slim profile, the Penrose uses fewer larger bars, and is smaller in the overall size.

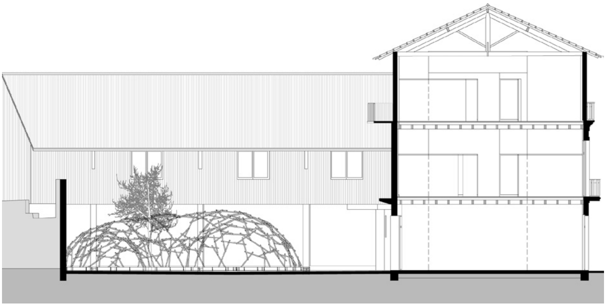
Finally, the structure generated based on the quadrangular mesh is characterized by a rectangular perimeter that is developed by lines parallel to the building limits. This design option had the purpose of unifying the building and the courtyard volumes, proposing the existence of support points in the northwest and northeast façades, in the southwest wall and in the ground in the southeast front of the patio. The structure is characterized by a large span that covers the most of the courtyard, and by being composed by a large number of bars with reduced dimensions (similar to the hexagonal structure). Although proposes a thin mesh the size of the span hinders its ability of self-support.

DESIGN AND MANUFACTURE OF THE STRUCTURE

The second phase of the workshop was focused on refining and detailing the design project and ultimately in building the reciprocal structure in the IDEGUI courtyard. For this purpose, the reciprocal structure proposal based on the hexagonal mesh was selected.

In order to adequate this proposal to some feasibility constrains, we started by reducing the number of bars and the global dimension, approaching it, in a certain way, to the structure generated from the Penrose mesh. The principles of implantation of a curvilinear perimeter and the placement of two access points to the interior of the structure were maintained, allowing its circulation around the tree (figure 7). Having as an objective the execution of the structure, it was relevant that all the knots of the hexagonal grid connected only 3 bars, as opposed, for example, to the quadrangular and Penrose grids.

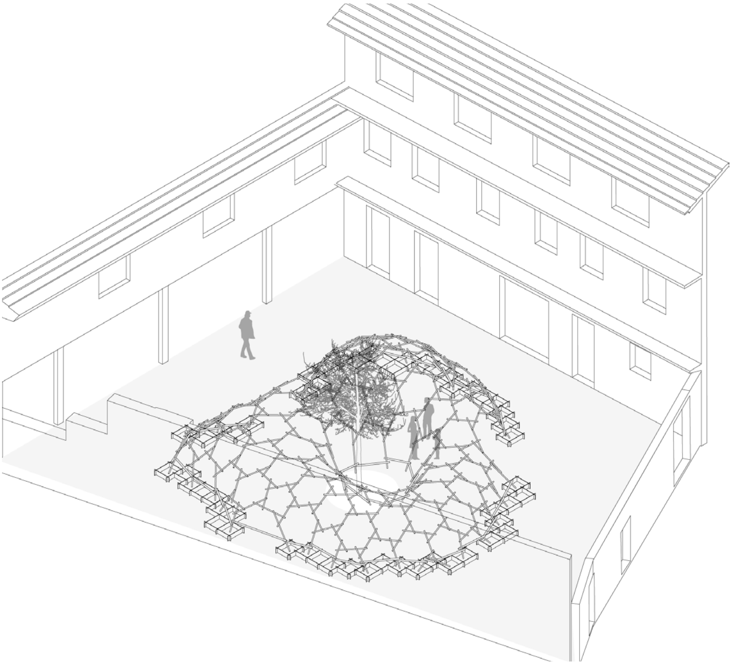




6. Plan implantation of the structure on the courtyard of IDEGUI

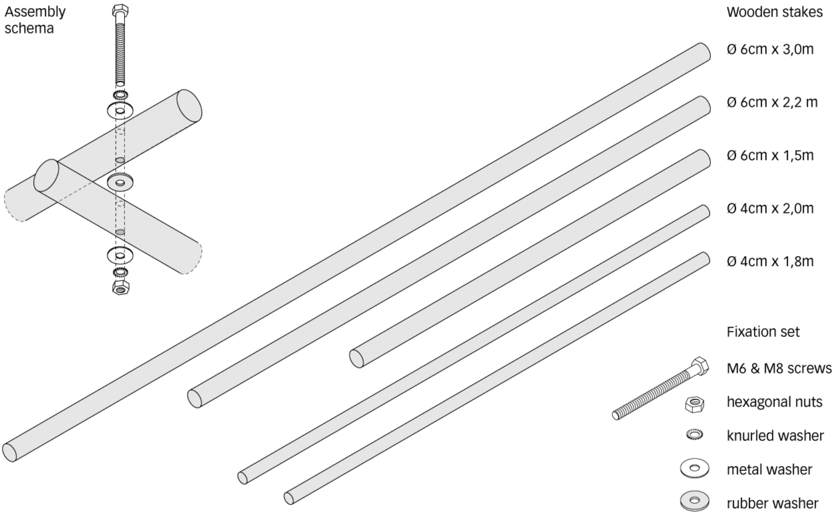
7. Elevation view illustrating the final version of the structure

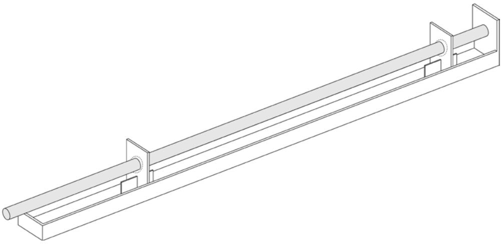
8. Axonometric view illustrating the final version of the structure

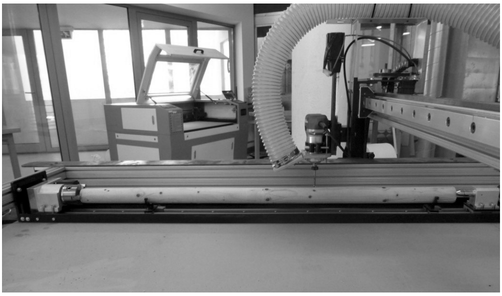


RECIPROCAL STRUCTURE DEFINITION

Once the initial mesh was defined (figure 5.a), it was decided that the positioning of the three constituent bars of each of the nodes would adopt the clockwise direction — the first bar would be set above the second, and so on. The generation of the reciprocal structure based on the Reciprocalizer was also constrained by the physical properties of the components of the bars — round pine-wood posts, normally used in the construction of wooden fences or stakes: maximum length of 3 meters, diameters of 4 cm, for the shorter bars, and 6 cm for the longer bars. This characteristics allowed to assign values to the parameters related to the eccentricity of the bars (e_{ij} = 4 cm) and the connection ratio (l_{ji} = 0,3) for positioning of the connections.







9. Schema and components used for the bars fixations/joints

10. Axonometry of the apparatus designed to mark the positions and angle of the drilling

11. CNC milling machine with of 4 degrees of freedom with automatic rotation axis

One of the syllabus goal was to demonstrate the capacity of this type of structures to define volumes with a high degree of formal freedom, capable of adapting to a specific context and of integrating an internal circulation. The initial mesh adopted and the solution generated allowed the reciprocal structure to inscribe in its interior a pathway with variable height that circumscribes the existing tree. And also to provide two porticos where is possible to enter and exit the structure.

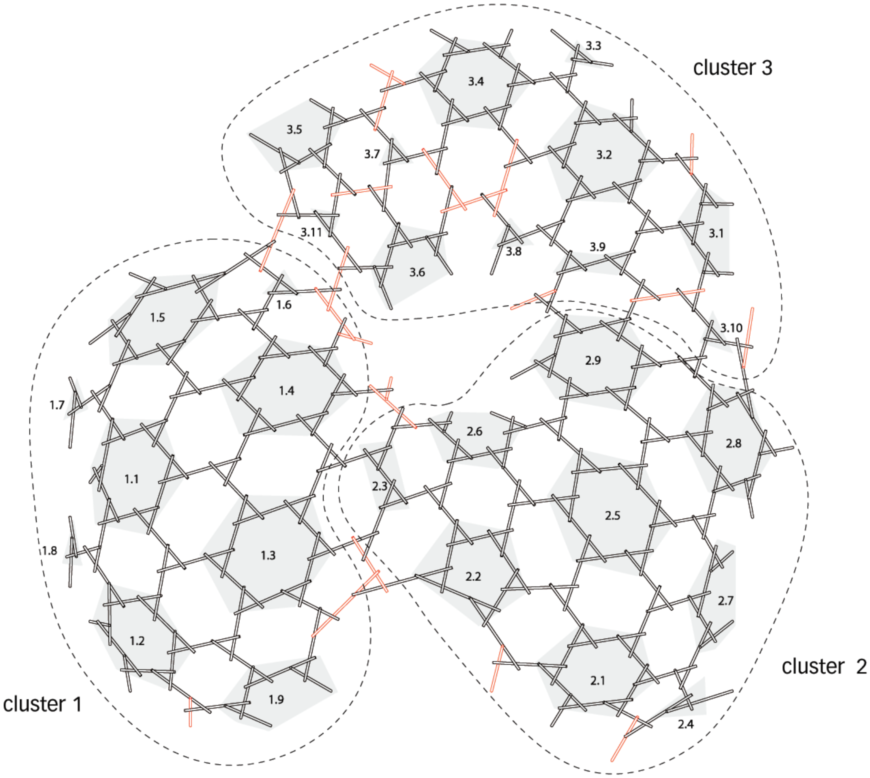
FOUNDATION SYSTEM

A system of foundations that could be easily assembled and disassembled was built to ensure that the anchor points did not move due to the structure's own weight. This also helped to compensate the unevenness of the patio pavement. The system consisted in a reticular grid with modules of approximately 80 x 80 cm, that followed the perimeter of the structure, where the anchor points were located. For this purpose it was conceived a system of boxes made from oriented strand board (OSB) filled with gravel. A fitting system without the need of mechanical joints was designed to speed up the manufacture and assembly tasks. As illustrated in figure 5.b the modular system considered variations in the components lengths in order to optimize the amount of material necessary for the execution of all the foundations.

STRUCTURAL COMPONENTS FABRICATION

The manufacture of the wood bars — linear components — was a process of three tasks: (1) systematization of the data relative to the dimensions of each joining elements; (2) marking of cut lines and drilling points for the entry of the fixing screws; (3) cutting, drilling and labelling the bars.

The first stage was realized with the help of a computational model developed in Grasshopper® that was able to gather all the information needed to produce the compo-



12. Plan showing the grid structure divided moduls and clusters nents. The output was a list defining each bar, containing the following data: length; connections position; angle of the four holes to be drilled at each node.

An apparatus was built in order to speed up the task of marking all the components (figure 10), a number of 242 bars of different dimensions, each containing four holes with different angles (888 in total). Subsequently, the operation was automated by installing a rotation axis in the IDEGUI 3-axis numerical control (CNC) milling machine (figure 11). The cutting of the posts was made by using a bench disk saw.

The cutting of OSB plates to manufacture the 123 parts that composed the foundation boxes was also performed with the help of the CNC milling machine.

ASSEMBLY PROCESS

A schema was depoyed for the planning of the subdivision of the overall structure into modules, nodes and fixing points. Since it is a light modular structure, most of the manufacturing and assembly tasks could be carried out by a group of 2 or 3 participants. Considering the large scale of the structure, prior to its assembly on the allocated site, a pre-assembly of modules was carried out. In general, each hexagonal module of the structural grid was constituted by six knots.

The fixing system of the joints was composed of M10 screws, in class 8.8 steel, and respective hexagonal nuts. In addition to metal washers at the ends, a rubber washer was included between the bars at the joint. Also in order to absorb any vibrations and torsions and to avoid loosening rotation of the screws, special washers for fixation were used containing internal teeth in the opposite direction of the slackening of the nuts.

The 53 foundation boxes provided a grid to locate the structure anchor points. Its assembly consisted in fitting the sliding joints from the 123 OSB panels. After the construction of the modules, the assembly of the structure started by taking as reference the location of the anchor points in the

13. Photos from the construction process ground. As illustrated in figure 12, at the time of fixing a set of modules, while a group of participants holds and guides the modules, a second group hold and guide a second module. A third group is responsible for screwing the bars in the joint knots. This process began with the construction of three autonomous clusters (figure 13), which were coupled in the final phase of the assembly. Finally, after the construction of the overall structure, the foundation boxes were filled with gravel.

SUMMARY

The main challenges and achievements for the conception and construction of a large-scale parametric reciprocal structure are presented in detail. In all the phases of this process a significant number of students of the Master in Architecture of the School of Architecture of the University of Minho, were involved. The aim of the initiative was to explore innovative concepts of architectural and structural design, including: research into methods and processes of design thinking mediated by parametric design processes, the use of advanced simulation tools and the exploration of concepts of fabrication and material handling.

Reciprocal structures arouse a growing interest in architectural schools because they constitute an experimental field of excellence. This event is intrinsic to the fact of their principles being suited to combine parametric de-sign tools and digital manufacturing with simple structural concepts allowing to achieve spatial structures with an high degree of complexity and appeal. In the workshop "Reciprocal Parametric Structures: Project and Manufacturing", a specific computational model was used to explore the generation of reciprocal structures from meshes with regular and irregular configurations — triangular, quadrangular, hexagonal, Penrose and other basic patterns. On the other hand, by the definition of computational models that automatically measure and quantify all the constituent components of the structure and through the use of digital manufacturing,

14. Final structure, photo by Inês Guedes a process of mass customization was produced. The workshop allowed the students to experience the formal potential of reciprocal structures, and to learn how to manipulate a new design methodology mediated by digital tools. Also this project offered the students a complete approach to a design process that promotes a linear integration of all the design stages from conception to construction.

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Design Institute
Spatial Structure

photographs by
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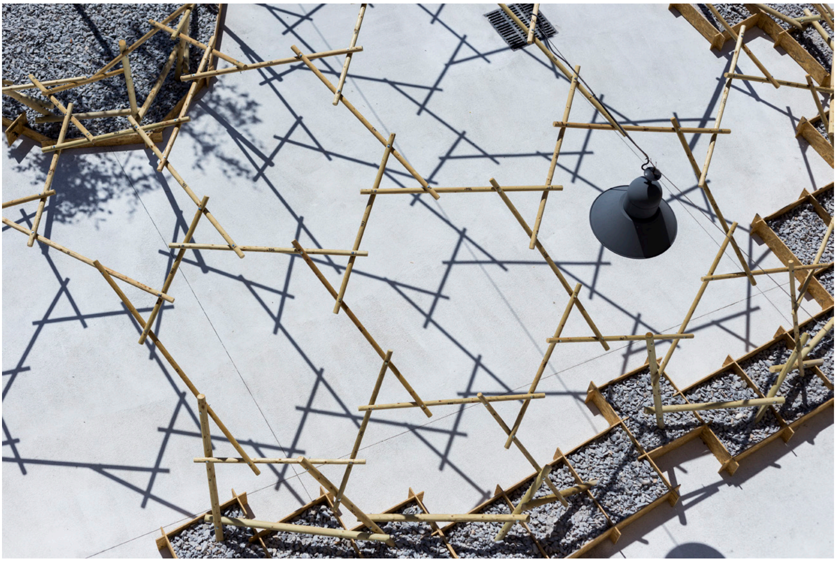

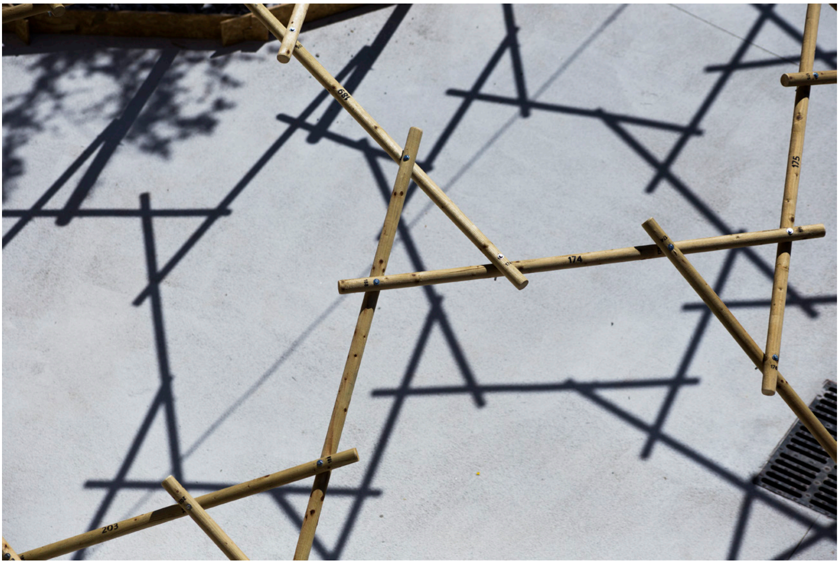

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DON'T TOUCH


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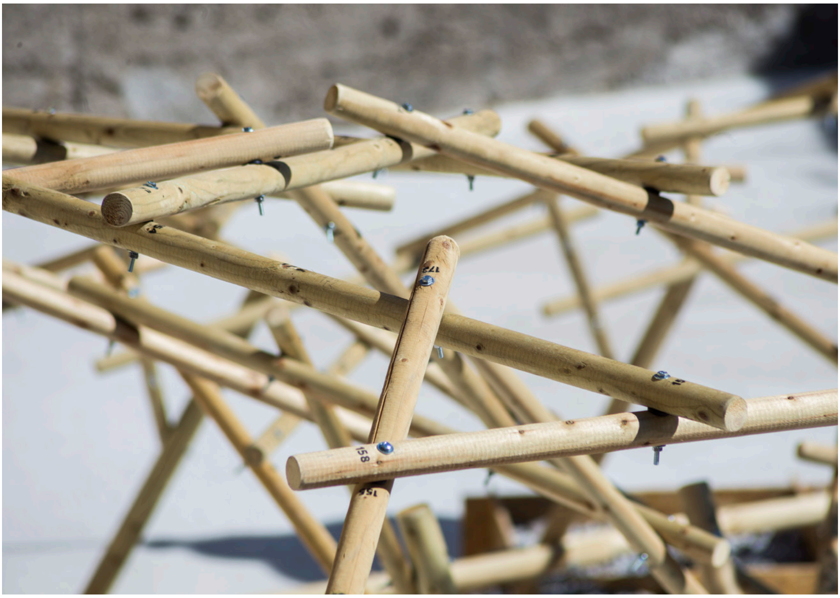
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