Innovation in Timber Architectural Structures and Digital Fabrication: A Cartography

Antonio J. Lara Bocanegra, Antonio Roig Vena, Ismael Dominguez Sanchez de la Blanca, Jose Perez de Lama

Antonio J. Lara Bocanegra, Fab Lab Sevilla - Universidad de Sevilla
Sevilla, Spain
antoniolara@us.es

Antonio Roig Vena, Universidad de Sevilla

aroigster@gmail.com

Ismael Dominguez Sanchez de la Blanca, Universidad de Sevilla

Sevilla, Spain

ismadubi@hotmail.com

Jose Perez de Lama, Fab Lab Sevilla - Universidad de Sevilla
Sevilla, Spain
perezdelama@us.es

Abstract

After a relative decline during Modernism, the use of large-scale timber structures is becoming a growing trend at the beginning of the 21st Century. Different vectors converge to make this happen. The most relevant of these vectors being the increasing technification and diversification of wood products as construction materials, such as micro-laminated and cross-laminated panels, the contemporary demands around sustainability, and the development of digital tools to design, simulate and fabricate innovative and efficient architectural structures that take advantage of timber properties. The present paper analyses the complex panorama of recent works approaching them from the point of view of resistant structure and form generation.

Keywords

Architecture, timber structures, digital design, digital fabrication, form generation

1 Introduction

We are experiencing today an increasing trend in the use of timber as structural material in architecture. Various vectors converge to promote this trend, pointing to its continuous use in the next future as a “new” technological material (Morel, 2008. Ross et al., 2009.).

Main vectors contributing to this increasing use of timber in architectural structures identified in this research are (Figure 01):

1. the continuity of traditional know-how concerning construction and structural typologies and detailing;
2. the development of new wooden-based materials with improved properties that stimulate typological innovation (such as cross-laminated and micro-laminated elements with high mechanical resistance that make possible multiple-storeys wooden constructions);

3. the emergence of innovative architectural proposals related to new digital design and fabrication tools (new geometries);
4. the emergence, as well, of innovative structural concepts and models made possible by advanced computer simulation tools;
5. the growing social demand and desire for sustainable production processes and environments, to which certificated timber with its negative or low carbon footprint significantly contributes, - besides its other positive environmental features.

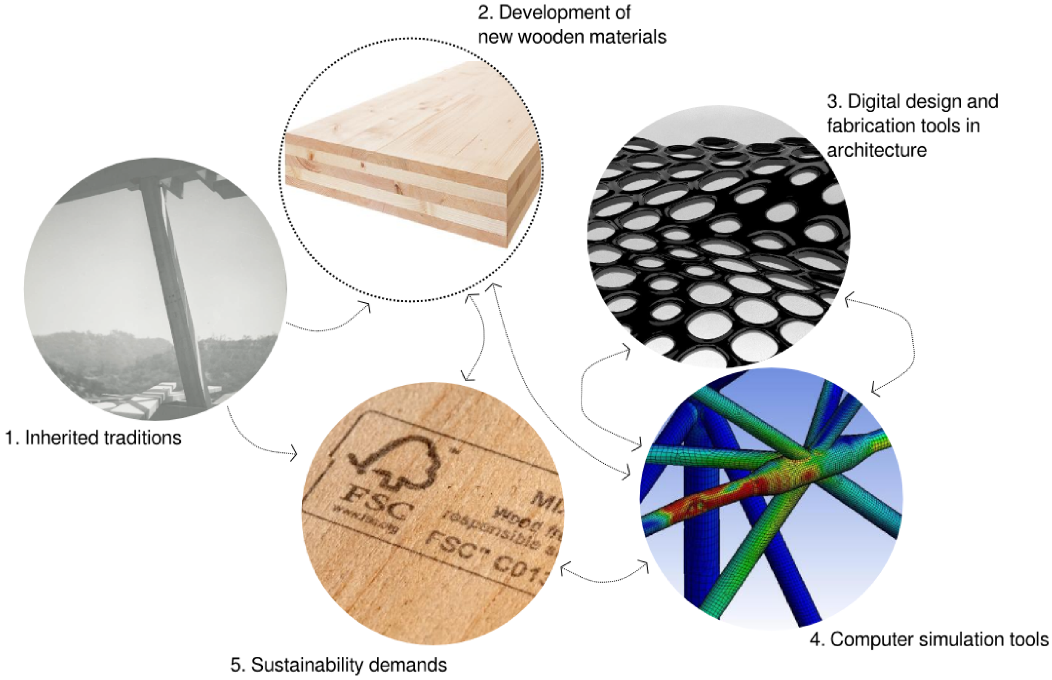

Figure 01: Diagram with main vectors promoting increasing use of timber in architectural structures (Lara & Pérez de Lama, 2014)

However, the multiplicity and heterogeneity of strategies and productions make it difficult to build a clear understanding of the state of the art in the field and its virtual unfolding. It seems adequate therefore trying to produce a cartography identifying relevant lines of work and relationships among them. There would be, of course, multiple ways to address a cartography on the topic. The perspective presented here considers strategies of form generation particularly related to architectural (resistant) structures. This is an architectural point of view that considers form and resistant structure as intimately related components of Architecture. This approach is stimulated by Spanish architectural tradition where design and engineering are not separated, but integrated in educational curricula and professional practice.

Additional perspectives to build further cartographies on the topic could consider scale and building uses, types of wooden materials, structure-envelope relationships, software tools employed, digital fabrication processes involved and types of joints used, among others.

2 Research process

The research process departs from a survey of contemporary architectural design publications that allowed for an initial selection of case studies. Criteria for this selection were double-fold. First, cases were chosen that combined architectural and structural design of recognized quality; second, the selection should provide a set of case studies showing a variety of approaches.

Case studies were developed as part of a course at the Higher Technical School of Architecture, lead by Lara Bocanegra (2012/2013), - lecturer at the *Estructuras Arquitectónicas* Department, University of Seville. As part of the guided students' work, case studies were reverse engineered, developing parametric definitions (using Rhinoceros and Grasshopper) and digitally fabricating structural scale models. Students were supervised in the process by Structural Engineering faculty, parametric design tutors and the Fab Lab Sevilla technical team. Knowledge and documentation produced was used as the base to produce the present cartography, which was presented in a first version at an exhibition at the University of Sevilla (November 2013- January 2014).

3 Form Generation Strategies

The detailed development of case studies allowed to define four, tentative, main categories, plus subcategories within them, that permit a better understanding of the field. This categories can be used as well as design principles.

Categories and subcategories identified to produce the present cartography are as follow (see Figure 11 at the end of the text):

1. Form generation based on traditional structural types
    - 1.1. Canonical types implementations
    - 1.2. Analogue transformations of canonical types
    - 1.3. Digital, parametric transformations of canonical types
2. Form generation through visual-plastic procedures
    - 2.1 Graphic patterns
    - 2.2 Digital processing of complex sculptural forms
3. Form finding through digital processes
    - 3.1 Generative & algorithmic form finding
    - 3.2 Form generation departing from digital fabrication processes potentials and constraints; towards robotic fabrication
    - 3.3 Material computation

3.1. Form generation based on traditional structural types

> Each material has a specific distinct personality, and each form imposes a different tensional phenomenon. The natural solution to a problem – art without artifice -, optimal according to the set of previous conditions that originated it, impresses us with its message, satisfying, at the same time, the exigencies of technician and artist. (Torroja, 2007: 11).

Structural types, understood in the wide sense used by Torroja, offer valuable information, not only about their structural behaviour, but also, about materials and execution processes.

Knowledge about the laws, constraints and freedoms allowed by structural types, as well as about specific timber properties as structural material, allows for an immense variety of architectural design options, that can simultaneously satisfy architectural, structural and execution needs.

We find indeed multiple designs based on this strategy, that go from a direct adoption of pure structural types, to analogue and digital transformations of those.

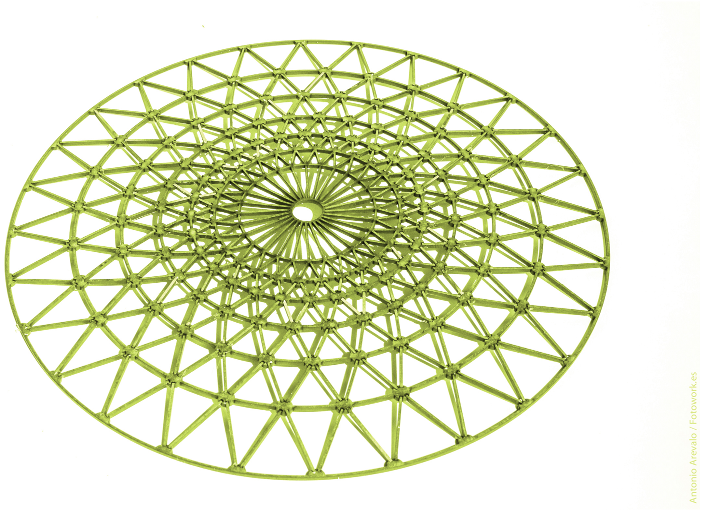

Figure 02: Centro Comercial Las Arenas, Barcelona (2011), Alonso-Balaguer with Rogers Stirk Harbour + Partners; dome structure scale model.

3.1.1. Canonical types implementations

The most elemental procedure consists in directly applying a structural type in its purest form. This is well suited, if not absolutely necessary, in large structures with significant stresses or deformations, where structural optimization becomes of paramount relevance. A clear example of this is the timber dome at *Centro Comercial Las Arenas*, in Barcelona, by Alonso-Balaguer in collaboration with Rogers Stirk Harbour + Partners, 2011 (Figure 02). Its structural diagram exactly corresponds with the *Trimmed Lamella Dome*, one of the classic diagrams to solve large-scale domes with single-layer grids (University of Surrey, undated).

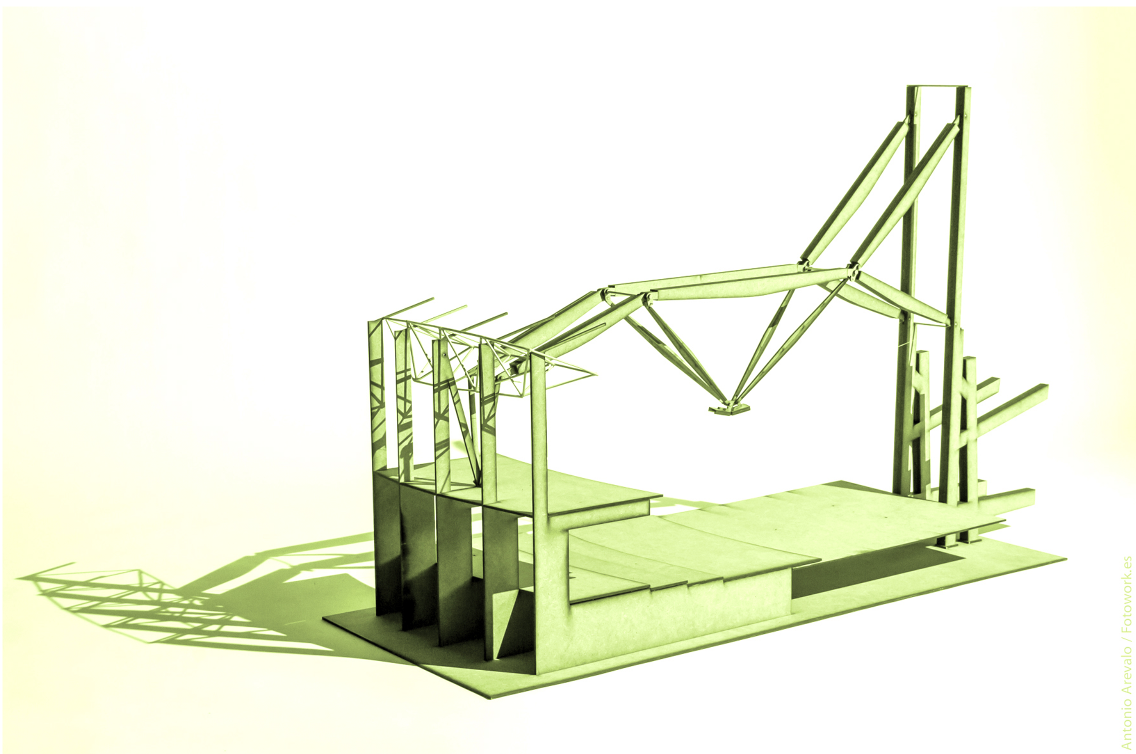

Figure 03: Scottish Parliament, Edinburgh, (2004), EMBT; structural scale model.

3.1.2. Analogue transformations of canonical types

Structural types transformations, adapting them to specific architectural requirements, considered from the beginning of the design process, - usually managing successive approximations through scale models -, offers infinite possibilities. This strategy has been widely used in international architectural production. Relevant examples include such different projects as the main meeting room of the *Scottish Parliament* in Edinburgh by Barcelona firm EMBT, 2004 (Figure 03), the *Palmyra House* in India by Studio Mumbai, 2007, the *Kiké House* in Costa Rica by Gianni Bostford Architect, 2007, or the *Tamedia* office building in Switzerland by Shigeru Ban, 2013. These projects present creative manipulations of structural types as diverse as light frames, diagonal frames, heavy frames and triangular sub-tensioned trusses, adapting them to particular structural and architectural requirements. Use of digital technologies in these procedures are varied as well, going from the full analogue production of the *Palmyra House*, to a complete Computer Controlled (CC) industrialized production process in the *Tamedia* office building example.

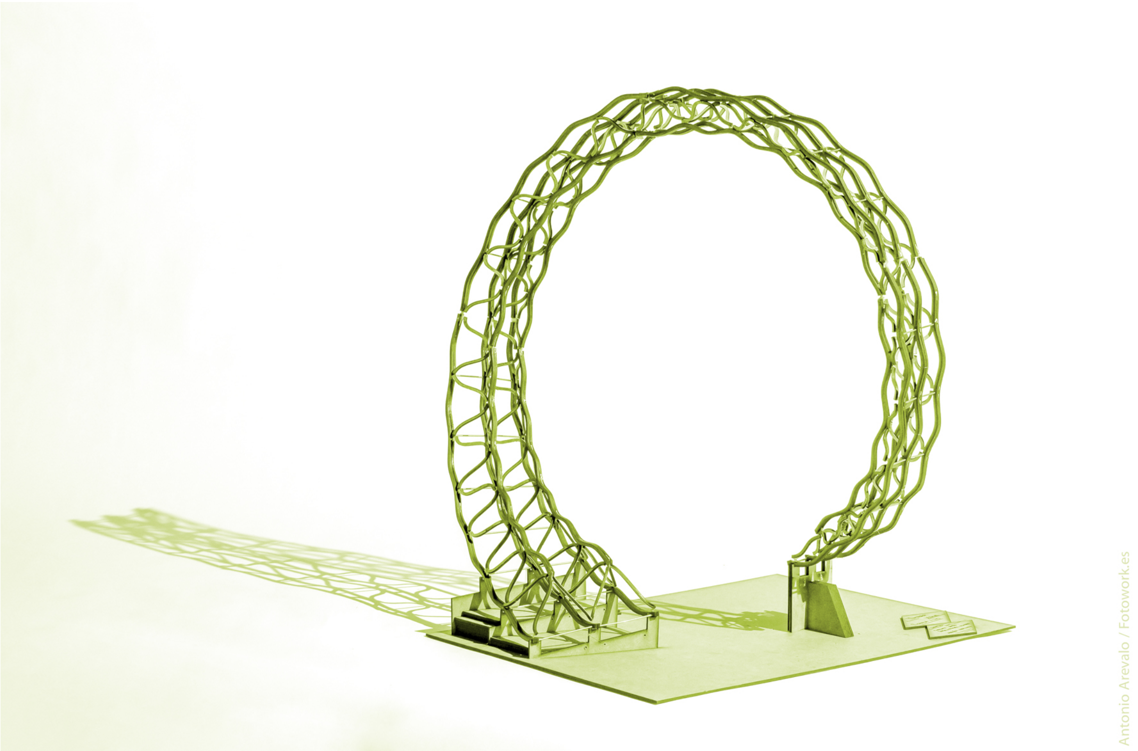

Figure 04: Timber Wave, London (2011), Amanda Levete and Associates; scale model by Fab Lab Sevilla students.

3.1.3. Digital, parametric transformations of canonical types

Cases within this sub-strategy include those works, that having chosen from the project start a particular structural type, its precise formal development is explored and found through transformations made on digital parametric models. In this way, the simple form of a structural type is transformed and adapted in order to fulfil specific architectural requirements, being able to reach levels of complexity not achievable through analogue procedures. A clear example of this strategy is the *Timber Wave* architectural installation by Amanda Levete, *AL_A*, designed for the Victoria and Albert Museum in London, 2011 (Figure 04). Here the designers transformed and adapted a double-layer grid into a helicoidal profile, generating a complex geometry made of multiple curved pieces each of them with a specific dimensionally different shape.

However, beyond making more or less interesting complex shapes, the true potentiality of parametrization lies in the generation of families of possible formal alternatives. Defining models through analytic geometry instead of descriptive geometry becomes one of the important changes in the design process made possible by new design tools.

The proposal by Iaac (Institute for Advanced Architecture of Catalonia) for the international competition Solar Decathlon 2010 constitutes a paradigm in this sense. The *Fab Lab House* (Figure 05) digital model incorporates environmental parameters, such as impinging solar radiation, that allow to modify and optimize the geometry of its envelope and structure according to different latitudes and climatic conditions. In this way, the project combines the advantages of industrial and, personalized digital productions, actualizing the concept of mass customization.

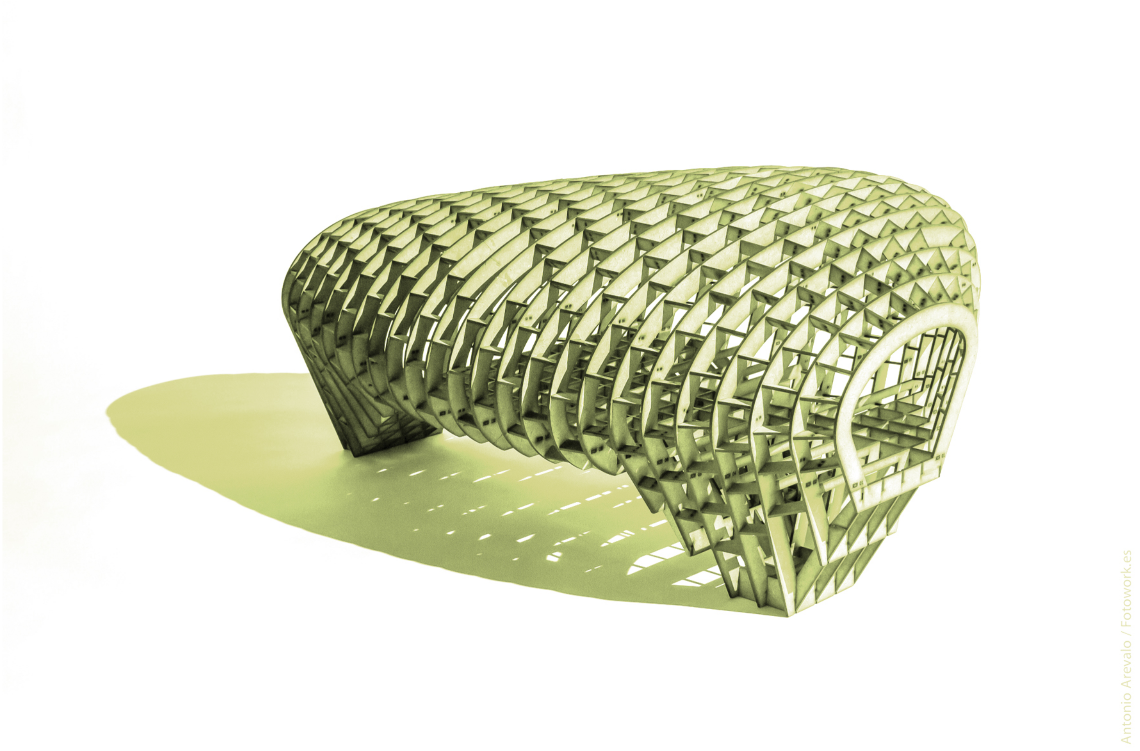

Figure 05: Fab Lab House, Madrid (2010), Fab Lab Barcelona and team; structural scale model.

3.2. Form generation through visual-plastic procedures

Purely plastic criteria, rather than structural, are often at the origin of contemporary architectural projects. Their main pursuit being to explore the materialization as architecture of graphic patterns, - planar or three-dimensional -, or strictly sculptural forms. Even if resulting resistant structures might have, sometimes, relations with traditional structural types, their origins, from the point of view of form generation, lie in the visual-plastic field.

The evolution of structural analysis tools and digital fabrication machinery allows now for the design, engineering and construction of virtually any complex form with high levels of precision, significantly expanding the possibilities of this kind of strategies.

3..2.1. Graphic patterns as form generation devices

This case deals with graphic patterns that are projected on a surface to become structural elements. Digital design tools are used to define patterns and surfaces and to project the former on the latter. Typically these structures present numerous crossings that make systems function as grids, as the surfaces where patterns are projected upon, most often don't have optimal geometries to allow them to function as shells. Therefore, this kind of solutions usually need tall sections of structural elements and high-rigidity solutions at joints.

Examples of this strategy are the *Haesley Nine Bridges Golf Clubhouse* in South Korea, 2010, and the *Pompidou Center-Metz* in France, 2010, both by architect Shigeru Ban.

In those particular cases where the surface is planar, the projection process is simplified. However, given that no rigidity is provided by the planar surface, in these situations, the joint design becomes critical.

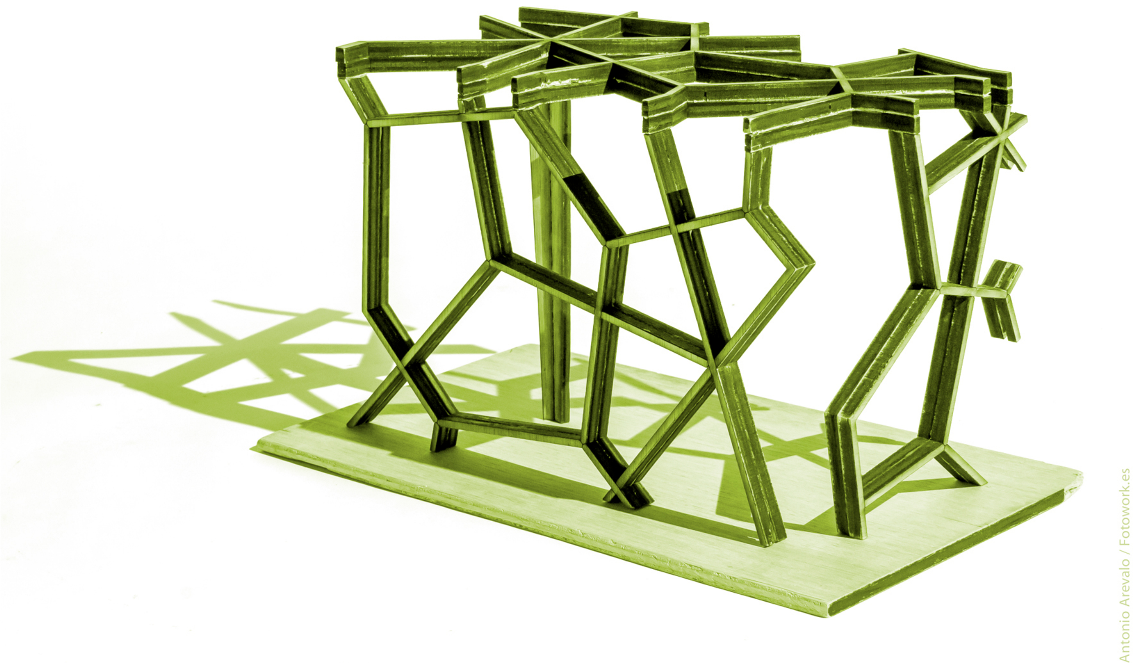

Figure 06: Sumika pavilion, Tokyo (2008), Toyo Ito. Structural scale model.

The *Sumika Pavilion* in Japan, by Toyo Ito, 2008 (Figure 06), illustrates this situation (Figure 06). An algorithmically generated planar pattern, - that evokes blossoming cherry trees -, defines the supporting structure of walls and roof. The structure was made in laminated wood with glued joints, reinforced with steel bars and epoxy resin.

3.2.2. Digital processing of complex sculptural forms

This strategy performs digital geometric operations on a given volume, with a sculptural character, with the aim of providing it with constructive and structural support.

These kind of operations (multiple sections, radial or parallel, etc.) that are performed by software tools, are useful and efficient at the smaller scales of furniture or ephemeral architecture, allowing for the construction of complex forms through simple procedures, as would be the cases of the *Dunescape* installation at MoMA/PS1 New York, by Shop Architects, 2000, or the *Ekko* installation by Thilo Frank in Denmark, 2012. However, when it comes to larger scale structures, significant difficulties may arise in the structural and constructive project resolution, affecting joint design as well as the actual choice of structural materials. These issues can be appreciated in the, otherwise spectacular, *Metrosol Parasol* project in Sevilla, Spain, by Jürgen Mayer, 2011 (Figure 07).

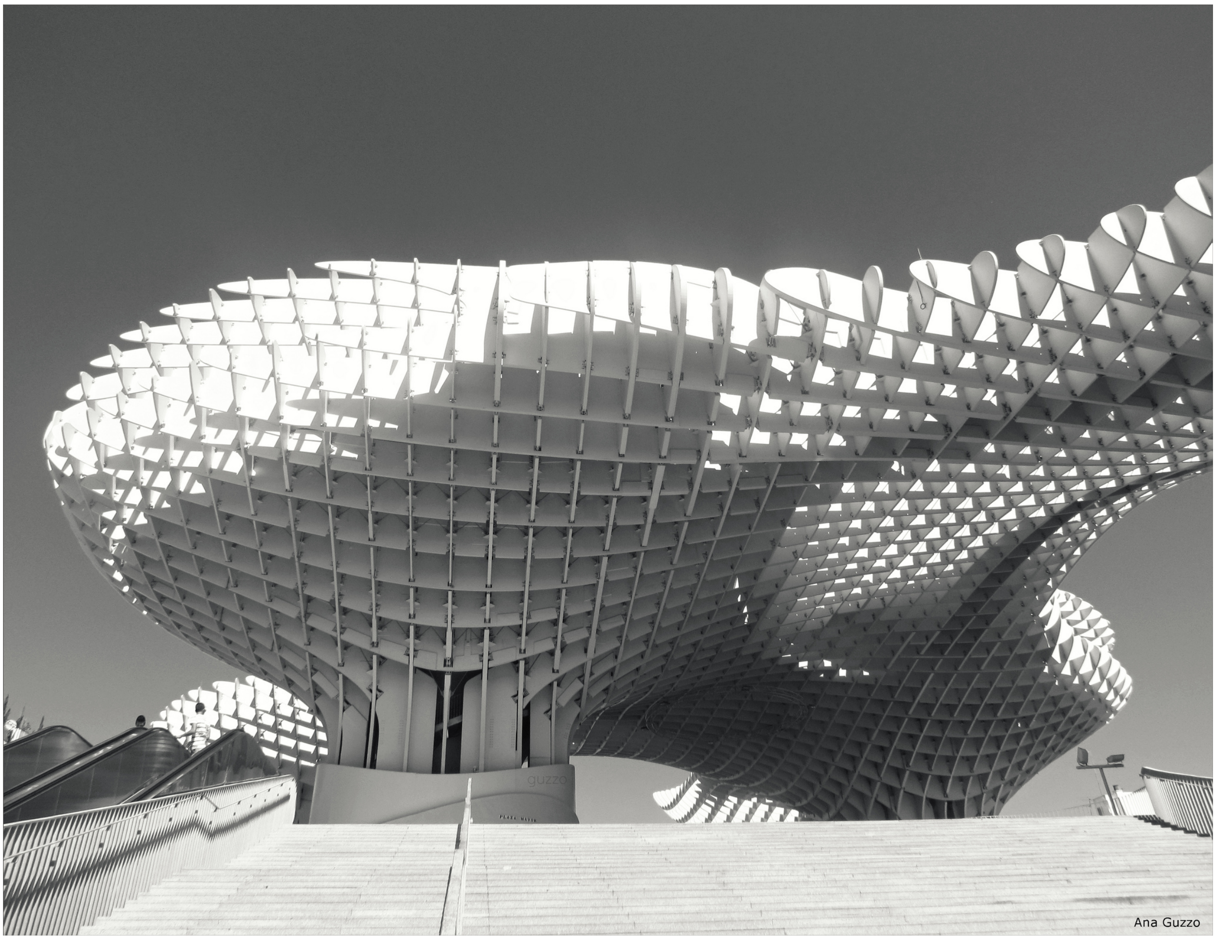

Figure 07: Metrosol Parasol, Sevilla, 2011, Jürgen Mayer. Photograph: Anna Guzzo; flickr.com.

3.3. Form finding through digital processes

Structural form finding through geometric and material experimentation and research has been widely explored throughout the 20th Century in academic, artistic, architectural and engineering milieux. Results of these processes being new structural types such as membranes, cable grids, tensegrities, and in the particular case of timber structures, Frei Otto's celebrated grid-shells – grids made with timber laths that keep their shapes due to the pre-stressing generated by the laths' elastic deformation (active bending).

Recently, with the evolution of digital tools, including programming and algorithmic components, experimentation has shifted, to a great extent, into the realm of computer and CC fabrication technologies. In this new framework, interest focuses on designing processes and behaviours rather than on searching for particular final results. In the structural field these strategies require research on the interaction of design & behaviour simulation tools, digital fabrication processes and structural-mechanical analysis tools.

This new integrative approach receives the name of *New Structuralism* (Oxman et al., 2006), and is being pursued by multidisciplinary teams in advanced engineering firms (Balmond, 2002), as well as in academia. In academia, works often materialize in the fabrication of experimental pavilions, most of them built in timber

(Gramazio et. al. 2008; Menges, 2012). We propose to classify form generation processes in this section in three different sub-strategies.

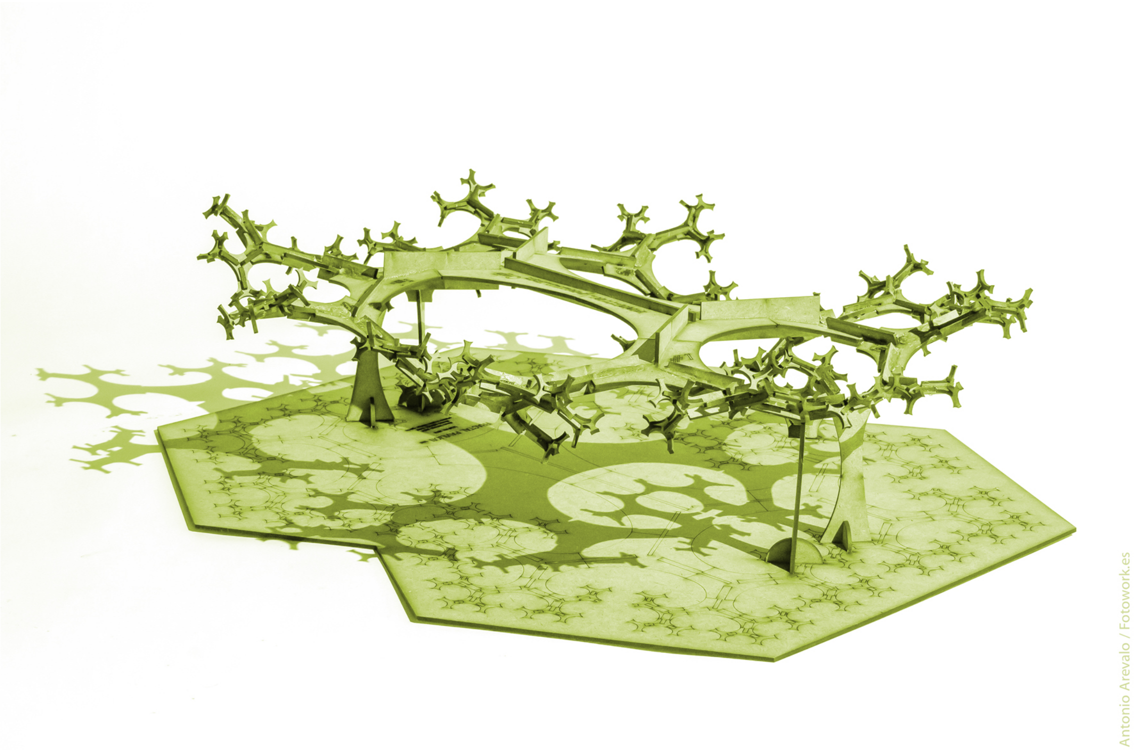

Figure 08: AA Summer (Fractal) Pavilion, London (2005), Architectural Association, Charles Walker and Martin Self; structural scale model.

3.3.1. Generative & algorithmic form finding

These strategies are based upon concepts coming from the areas of mathematics and geometry (branching, fractals, tessellations, Voronoi diagrams, etc.) and biology (morphogenesis, evolutionary processes, etc.). Typically these designs depart from simple elements and sets of behaviour and relationship rules that give way to growing geometries. These algorithmic simulations are finding a rich field of application in the realm of design, generating “non-euclidean geometric spaces, kinetic and dynamic systems” (Kolarevic, 2003), producing results not a-priori known by their authors. In the morphogenetic approach, generative rules seek to include structural and other constraints into the system evolution, seeking to create growth processes similar to those of living organism (Hensel et ali. 2010).

The *Fractal Pavilion*, fabricated in 2005 by Architectural Association students with the coordination of Charles Walker and Martin Self, explores the application of fractal geometries, using algorithms that multiply and spatially distribute, through simple operations, structural elements (Figure 08). Even if this procedure hasn't given yet significant results using timber at a larger, architectural, scale, interesting developments should be expected. For example, through its application to spatial grids generated out of complex polyhedral formations, such as those explored in the *Grotto* project by Benjamin Aranda and Chris Lasch in collaboration with Ove Arup's *Advanced Geometry Group* (Aranda del al., 2005).

3.3.2. Form generation departing from digital fabrication processes potentials and constraints; robotic fabrication

Structural form may be generated by the definition of joint solution and assembly process. Through this, an architectural work can be conceptually defined, as well as in its construction details and overall character. Algorithmic development allows for the description of the initial constructive/fabrication concept (incorporating material properties in the model) and its adaptation to each specific situation or instance.

The *Serpentine Gallery Pavilion* in London, designed by Alvaro Siza and Eduardo Souto de Moura, 2005, explored this kind of process. Departing from a simple module, based on the sequential structure concept invented by Leonardo da Vinci, and designing a variation of the traditional mortise and tenon joint, Siza and Souto de Moura, – again in collaboration with Arup engineers -, generated a complex overall geometry answering project requirements such as transparency, circulation and connection with the surrounding areas. Their concept allows for the design of complex geometries using planar, and relatively small sized elements. Pieces are CC machined making possible high geometric precision and tight assembly control – which could be even tighter if the assembly process were to be managed digitally.

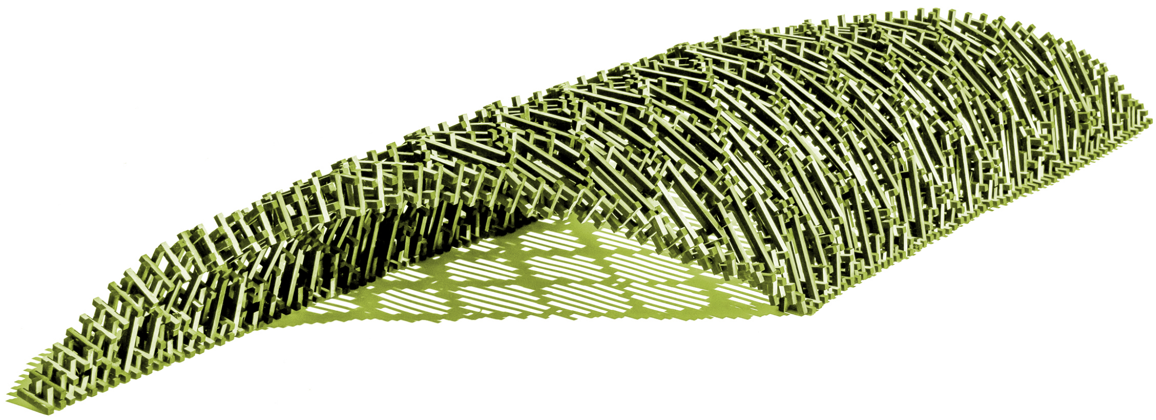

Figure 09: Sequential Pavilion, Zürich (2010), Gramazio & Kohler / ETH Zürich; simplified scale model.

That is the research field of Swiss-based team Gramazio & Kohler. Their proposal consisting in the design of assembly processes using robotic arms that interpret the algorithm that define the actual form generation sequence. The *Sequential Pavilion* (Figure 09) was produced as a result of a course led by Gramazio and Kohler at ETH Zürich, 2010, dealing with a process of adding small glued timber pieces (with constant section) performing a structural role. Adaptation of the predefined construction rules to a double curvature anti-funicular overall geometry generated rigidity and efficiency. An algorithmic definition provides the length of each of the pieces, its relative position and allows for a fast and precise fabrication process, performed by a robotic arm. In later courses (2013) the concept was extended to produce further structures with apparently aleatory geometries, that received the name of *Spatial Aggregations*.

3.3.3. Material computation

Conventional structural design processes developed with digital tools involve two different phases. A first one dealing with geometric definition, and a second one dealing with structural-mechanical analysis. With this procedure, nor mechanical material properties neither physical laws are explicit components of the initial part of the process. As an alternative to this two-phases procedure, the *Institute of Computational Design* (ICD), University of Stuttgart, lead by Achim Menges, is developing structural timber proposals where elastic and resistant properties are coded into design models. This way, generated geometries become expression of their material structural behaviour. This kind of digital modelling based upon elastic properties of materials represents, according to Menges (2012), a true revolutionary shift from digital design to computational design.

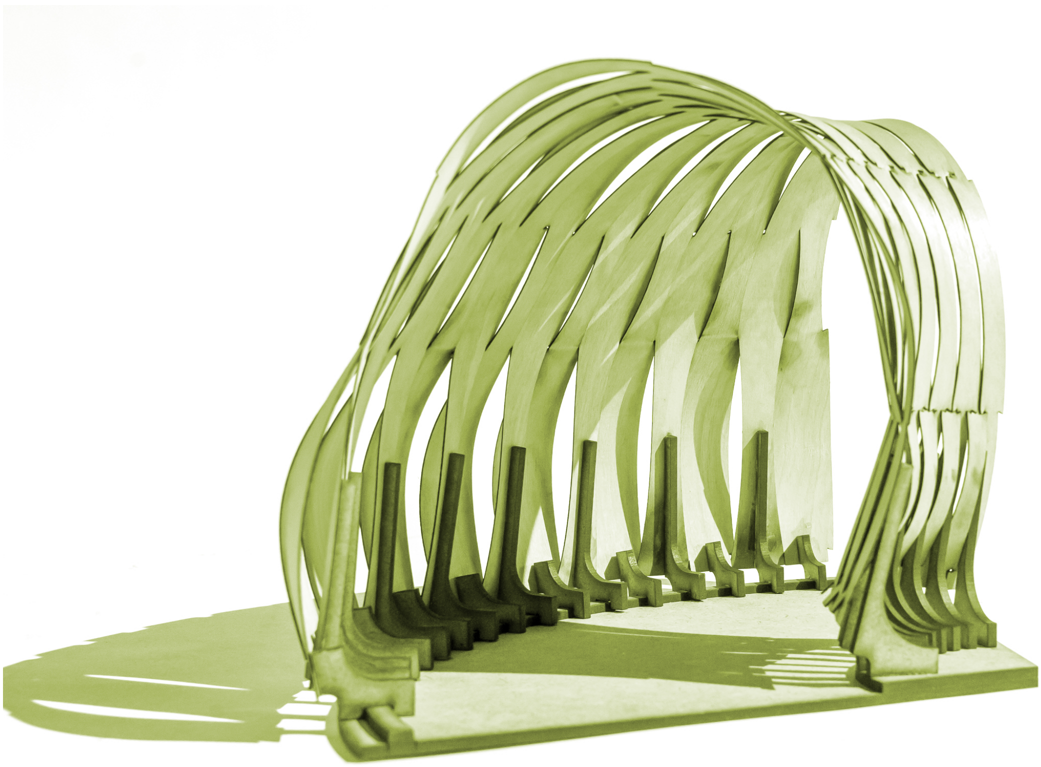

Figure 10: ICD/ITKE pavilion 2010, Suttgart, Achim Menges and team; structural scale model; section.

This is the case of a pavilion developed by ICD in collaboration with the *Institut für Tragkonstruktionen und Konstruktives Entwerfen* (ITKE) in 2010 (Figure 10). It was a research process on plywood panels, which extended into the digital realm analogue works developed by Frei Otto on active bending. The 2010 ICD/ITKE pavilion explores digital simulation of multi-layered wooden panels as affected by perforations and discontinuities before the bending process. Other researchers, including the Barcelona team *Coda Office* (Soriano et al. 2014) and the *EmTech* program at the Architectural Association, London, in collaboration with Menges (Hensel, 2010), are exploring similar situations.

The *Pudelma Pavilion,* a collaboration between Columbia and Oulu universities, built in Turku, Finland, 2011, represents another interesting instance of this kind of strategies. Its design incorporates the effect of gravity on materials with no flection rigidity. The design recovers structural generation processes developed by Gaudi, and later by Otto (in which resistant shape was obtained by reversed load funiculars), combining them with local carpentry traditions. The resulting design was a timber structure that supports only compression stresses, allowing for very simple connections efficiently solved with mortise and tenon joints.

4 Conclusions

The cartography presented in this paper deals with innovative form generation strategies in timber architectural structures. Application of timber in architecture is experiencing an significant renovation, due to technological evolution and sustainability concerns. In the context of Fab Labs, the main interest of the paper is in extending Fab Lab activities into the architectural scale. It might be mentioned that in Spain, where the study is produced, architectural design and structural engineering are not independent activities, but are integrated in educational curricula and professional practice.

The present cartography orders an apparently chaotic panorama, allowing for a better understanding of the field evolution and relationships between different contemporary approaches. This ordering can be a good tool in educational environments. A further step in this research would be to generate specific work-flows and protocols for the application of the different identified design strategies.

The family of strategies united under the tag of digital form finding is a very rich and diverse field, that should be explored and described in much finer detail than has been done here.

Of course, other cartographies could be produced, considering different criteria than those applied here. Among others, in the context of Fab Labs, it would be of interest to develop a classification of architectural design and fabrication strategies according to their “fab-ability”, that is, their susceptibility to be developed using the conventional Fab Lab tools and machines.

Acknowledgements

The present text is a translated, extended and updated version of a former one by A.J. Lara Bocanegra, A. Roig Vena and I. Domínguez Sánchez de la Blanca, 2014 (see references). Architectural models in images illustrating the text have been fabricated at Fab Lab Sevilla by students of the Higher Technical School of Architecture University of Sevilla (2013). The authors would like to thank them, as well as the architects and designers of the various architectural pieces commented in this work. Photographs of models are by Antonio Arévalo / fotowork.es.

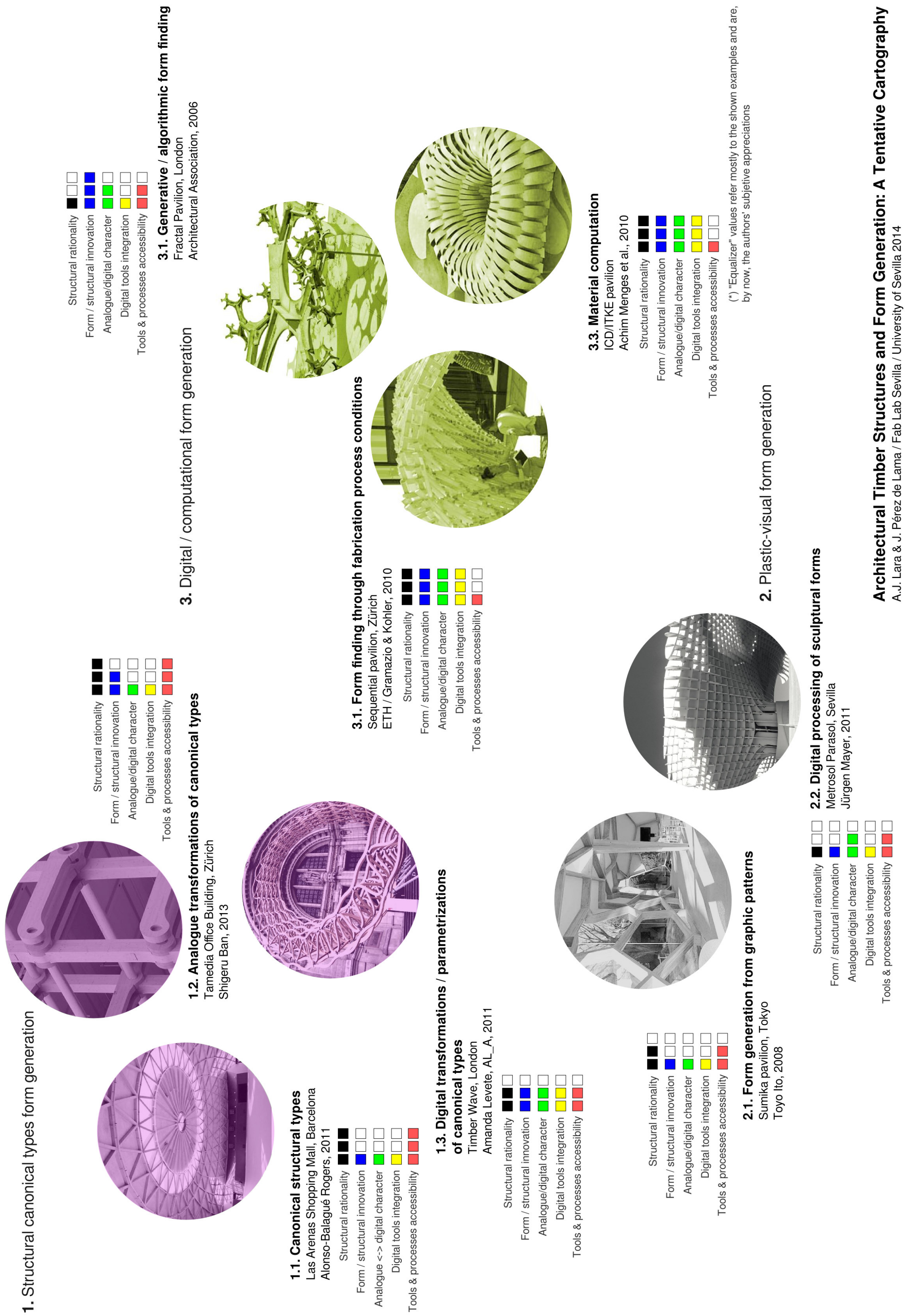

Figure 11: Cartography of innovation in architectural timber structures and form generation (Lara and Pérez de Lama, 2014).

References

Aranda, B., Lasch, C., (2005). Pamphlet Architecture 27: Tooling. New York: Princeton Architectural Press.

Balmond, C., Smith, J., (2002). Informal. Munich: Prestel.

Bernabeu, A., (2007). Estrategias de diseño structural en la arquitectura contemporánea. El trabajo de Cecil Balmond. PhD Thesis Universidad Politécnica de Madrid.

Bostford, G. Architect. Casa Kiké. Retrieved 27 June 2014, from http://www.giannibotsford.com/project/casa-kike/

Dempsey, A., Obuchi, Y., (2010). Nine problems in the form of a pavilion. London: AA Publications. Architectural Association.

Gramazio F., Kohler, M., (2006). Digital materiality in Architecture. Zürich: Lars Müller Pubslishers.

Hensel, M., Menges, A., Weinstock, M., (2010). Emergent Technologies and Design. London: Routledge.

Instituto de Arquitectura Avanzada de Cataluña. Versión Septiembre 2010, (2010). FabLab House. Proyecto de ejecución para la competición Solar Decathlon 2010”. Barcelona.

Kolarevic, B., (ed.), (2003). Architecture in the Digital Age: Design and Manufacturing. New York: Tayler and Francis.

Lara Bocanegra, A.J., Roig Vena, A., Domínguez Sánchez de la Blanca, I., (2014). *Estructuras de madera. Procesos de génesis. Diseño computacional y fabricación digital*. In: Pérez de Lama, J. et al. (eds.). Yes We Are Open! Fabricación digital, tecnologías y cultura libres. Sevilla: RUBooks; p: 98-113.

Menges, A. *Material resourcefulness. Activating material Information in Computational Design*. In: AD Material Computation. Higher Integration in Computational Design, Num. 216. March/April 2012; pp: 34-42.

Morel, P., (2008). Research on the Biocapitalist Landscape. In: Wang I. (ed.), Verb Natures. Barcelona: Actar; pp: 224-245.

Otto, F., (2008). Conversación con Juan María Songel. Barcelona: Gustavo Gili.

Oxman, R., Oxman, R. The New Structuralism: Design, Engineering and Architectural Technologies. In: AD The New Structuralism. Design, Engineering and Architectural Technologies. Num. 206. July/August 2006; pp: 14-22.

Ross, P., Downes, G., Lawrence, A., (2009). Timber in Contemporary Architecture: A Designer's Guide. London: TRADA Technology, RIBA.

Self, M., Walker, C., (2011). Making pavilions. London: AA Publications. Architectural Association.

Songel, J. M., (2005). Frei Otto y el Instituto de Estructuras Ligeras de Stuttgart. Una experiencia de metodología, investigación y sistematización en la búsqueda de la forma resistente. Phd Thesis. Universidad Politécnica de Valencia.

Soriano, E., Tornabell, P., (2014). CODA (Computational Design Affairs). In: Pérez de Lama, J. et al. (eds.). Yes We Are Open! Fabricación digital, tecnologías y cultura libres. Sevilla: RUBooks; p: 90-97.

Torroja, E., (2007). Razón y ser de los tipos estructurales. Madrid: CSIC Ministerio de Fomento CEDEX-CEHOPU.

University of Surrey. What is a space structure? Retrieved 27 June 2014, from http://portal.surrey.ac.uk/portal/page_pageid=822,568927&_dad=portal&_schema=PORTAL

Willman, J. El ebanista digital. Hacia la fabricación robotizada. In: Arquitectuta Viva, Más madera. De la artesanía a la robotización. Num. 137. Madrid 2011.