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ALGORITHMIC THINKING

8

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Editors of the current issue: Ramón Sastre Sastre and Ana Cocho-Bermejo

The current issue is dedicated especially to a very special colleague, friend, mentor and member of our scientific committee who left us early….
Farewell dear Edith

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Algorithmic Thinking

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The 8th issue of the **archiDOCT** e-journal gathers papers that explore the idea of relational thinking in architectural design. The main aim of the issue is to highlight doctoral research work that deals with design processes of open-ended scenarios where information technology plays a key role. Nowadays there seems to be a consensus about the current issues recurring in design: continuous variation and intelligent emergence towards variability that is explored through computation. The variability yielded through the exploitation of computation allows for new design methodologies to emerge that in turn suggest new formal languages. In this sense the current architectural narrations assert for a dynamic conception of form. The notion of architectural form as interface, emerges as a crucial factor for design appling a real-time affection between architecture and people. Architectural design proposals are driven by a better consciousness of material behavioural possibilities aiming for formal enrichment. Architects might be looking at systems components and their interactions with each other in an attempt to find the basic definition of a new aesthetics. The integration of smart materials and the emergence of the constitutive automation model is important in this direction, as it leads to research that simplify control systems while augmenting form dynamics.

This time we have had the chance, the honour and the fortune to count on the text written by **Kostas Terzidis**, "The Intricacy of the Otherness". Kostas Terzidis, author of the book "Algorithmic Architecture", is a pioneer and a world-wide recognized expert on these subjects. In that book he coined the term algotecture to denote the use of algorithms in architecture. We are sure this text will give a new point of view to all the readers interested in **Algorithmic Thinking**, as well as to the contributors to this issue.

This **archiDOCT** issue shows doctoral research efforts focusing upon New Digital approaches system finding based, that have opened up the debate on a new aesthetics associated with the second phase of digital era we are currently experiencing. Authors are not only engaged with concepts as variability, parametric design, digital media, algorithmic design, continuity or digital materialization and fabrication techniques but also with concepts within the post-parametrics era and the definition of the respective discourse. Contemporary advances in systems based on the continuous variation triggered by the intelligence of their components interacting with each other, are currently proposed as the cause for the emergent properties that will configure architectural design.

In this direction, **Enrique Soriano**, PhD student at Barcelona Tech, UPC, explores and deepens into the field of gridshells in his text "Low-tech Geodesic Gridshell: Almond Pavilion". He believes that traditional gridhsells are extremely efficient but the erection complexity make them neither appealing for the industry nor accesible. This paper shows the research conducted on the universalization of the alternative irregular gridshells based on geodesic patterns, that enabled to build . The paper discusses the suitability for scarce budgets and low-tech manufacturing. Geodesic gridshells are defined and a low-tech implementation of a multilayered geodesic gridshell is presented.

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In a very different way, **Omar Avellaneda**, PhD student at Barcelona Tech, UPC, in his text "Deployable Structures System, Hexagonal X-frame - Three Case Studies", reproduces part of his research about methods to control the movement of the deployable structures with membranes. Using maximum stresses of this textile he tries to stabilize and control the movement of the deployable structures. The research proposes three case studies, from its geometrical design to the final realization of a low cost scale prototype. Supported by parametric design and physical models, he verifies the movement and geometry finally proposing to create support tools for the design of deployable x-frame structures with hexagonal modules.

Angelo Figliola, PhD student at La Sapienza (Rome), in his text "Post-industrial Robotics: The New Tendency of Digital Fabrication for Exploring Responsive Forms and Materials Through Performance" shows his research on robotics manufacturing issues on a 1:1 scale. The pavilions Fusta Robotics and Digital Urban Orchard and the technological system In. Flux are the results of tests in which material, environmental and structural performance inform the computational process and the consequent materialization. Fusta Robotics is the result of collaboration between industry and universities for the tectonic experimentation derived from the use of local non-engineered material. Digital Urban Orchard is the formal expression of a complex functional program arising from the relationship amongst form, function and context for a new concept of socialization space and food production within the agenda at the self-sufficiency in Barcelona. Finally, through the In.Flux prototype, he investigates the relationship among formal generation, structural analysis and robotic manufacturing for the realization of concrete free-form structures opening the debate on the role of IT in the post-digital era when the design process manifests through the control and management of the flow of information affecting the digital computation and fabrication and the material behaviour.

Another approach to the subject is presented by **Katerina Saraptzian**, PhD student at AUTH (Aristotle University of Thessaloniki). In her paper "Integrated Evolutionary Strategies on Structurally Informed Complex Grid Morphologies" presents an on-going research, which addresses the notion of algorithmic thinking in architectural design that can re-create efficient integrated design strategies. It focuses, in particular, on the notion of structural complexity and attempts to interpret it as a 'bottom-up' property that can inspire and facilitate the design of non-standard forms in architecture. Her experimental approach attempts to investigate a series of parameters that can dynamically affect the form-finding procedure of an irregular grid system and aims to generate evolutionary strategies on structurally informed complex morphologies. Those parameters are examined through their combination on a set of digital simulations, while the whole process is being computationally encoded and performed within the environment of Grasshopper.

Finally, **Natalia Torres**, PhD student at Barcelona Tech, UPC, in her paper "Deployable Arches Based on Regular Polygon Geometry" discusses a deployable-arch-structure design that is built using articulated bars, commonly called as scissor-system, based on regular polygon geometry. Deployable structures elude the need for these external supports greatly simplifying the assembly process and deployment time. In a point of her conclusions she says "parametric design has generated valuable solutions to the geometric concept, which results in more efficient design, manufacturing, and assembly. In addition, a new way to design deployable structures through variable geometric parameters has been developed".

Cover Image credits: Ana Cocho-Bermejo. *Proccesing studies for the 9 cubes problem*

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The Intricacy of the Otherness

Dr. Kostas Terzidis // CEO at Organic Parking, Inc

An algorithm is a process of addressing a problem in a finite number of steps. It is an articulation of either a strategic plan for solving a known problem or a stochastic search towards possible solutions to a partially known problem. In doing so, it serves as a codification of the problem through a series of finite, consistent, and rational steps. While most algorithms are designed with a specific solution in mind to a problem, there are some problems whose solution is unknown, vague, or ill-defined. In the latter case, algorithms become the means for exploring possible paths that may lead to potential solutions.

Theoretically, as long as a problem can be defined in logical terms, a solution may be produced that will address the problem's demands. An algorithm is a linguistic expression of the problem and as such it is composed of linguistic elements and operations arranged into spelling, and grammatically and syntactically correct statements. The linguistic articulation serves the purpose not only to describe the problem's steps but also to communicate the solution to another agent for further processing. In the world of computers, that agent is the computer itself. An algorithm can be seen as a mediator between the human mind and the computer's processing power. This ability of an algorithm to serve as a translator can be interpreted as bi-directional: either as a means of dictating to the computer how to go about solving the problem, or as a reflection of a human thought into the form of an algorithm. The latter one will be addressed in more detail later in this chapter.

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Traditionally, algorithms were used as mathematical or logical mechanisms for resolving practical problems. With the invention of the computer, algorithms became frameworks for implementing problems to be carried out by computers. While the connotation associated with the action of giving instructions, commands, or directions is subconsciously assumed to be aimed at a sentient worker, the computer, despite its once human identity, is not a human being and therefore should not be treated as such. (Perhaps it would be more accurate if a new name was given that would reflect more accurately its true potential, such as portal, transverser, or, hyperion[1].) By liberating the user of a computer from material concerns associated with labor, skill, or complexity or from emotional factors such as compassion, fatigue, or boredom computers can be utilized as tireless vehicles that allow humans to realize, overcome, and ultimately surpass their own physical and mental limitations. The significance of this liberation lies not that much in the amount of work that can be accomplished but rather in the fact that the human mind is in a position to invent devices that will help it exceed its own limitations. Furthermore, through such inventions such as the computer a world is encountered, that of applied computation, which, while intellectual in nature, abides to principles, mechanisms, and performances that lie beyond the realm of the human mind.

1.Hyperion means "beyond-one" and is also the name of a Titan, father of Sun, Moon, and Dawn who was considered to be the god of observation.

An algorithm is a set of instructions given by a human to be performed by a computer. Therefore, an algorithm can describe either the way a problem is to be addressed as if it would be resolved by a human or the way it should be addressed to be understood by a computer (the notion of "understanding" here refers to the capacity the computer has to process information given by a human and not to its conscious interpretation of that information). In taking the first case, an algorithm becomes a rationalized version of human thinking. As such it may be characterized as being precise, definite, and logical, but at the same time may also lack certain unique qualities of human expression such as vagueness, ambiguity, or ambivalence. While this may be true as far as the linguistic expression is concerned, it is not necessarily true for the products of the language. For instance, one can use unambiguous words to articulate an ambiguous statement, i.e. "the man saw the monkeys in his pajamas." In other words, the explicit nature of the statements that compose an algorithm do not necessarily also reflect the explicit nature of the output. Likewise, precise platonic geometrical shapes can be combined algorithmically to produce quite ambiguous geometrical forms. Just because the language elements or even the syntax is rational, it does not mean that the products will also follow the same trend.

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In the second case, an algorithm is seen as a linguistic expression fitted to the needs of the computer. As such it becomes an idiomatic language of conformity or adaptation to an alien reasoning. The word alien is used here not as a means of intimidation but rather as an indicator of an alternative, perhaps parallel, logic to that employed by the human mind. Contrary to common belief, a computer's logic, while seemingly a product of the human mind, is not a subset of it but rather a parallel, if not superset, to it. When inputting information in the form of an algorithm for a computer to process, one must adjust one's reasoning to the reasoning of the computer-worker and not to that of a human-worker. Certain qualities of the human mind such as those that contribute to what is considered "smart," i.e. sharpness, quick thought, or brightness, may not be desirable or even applicable when dealing with the computer's reasoning. What is considered to be smart in one world may be considered dumb in another world; this is precisely the reason why the two reasoning systems are parallel, complementary, or perhaps antithetical. For instance, to find a secret password a human may exploit context-based conjectures, reductive reasoning, assumptions, or even spying as strategies for saving time and effort. In contrast, a computer can solve the same problem by simply checking all possible combinations of all alphanumeric symbols until a match is found. Such as strategy, referred to as brute force, would be considered overwhelming, pointless, naïve, or impossible by a human investigator. Nonetheless, given the computational power of a computer such a strategy may only take a few seconds to check millions of possibilities, something inconceivable to the human mind.

The term inconceivable is used here to denote an inability to comprehend, and implicitly it refers to the human mind. Clearly, the term is figurative, metaphorical, or linguistic, for if it were literal it would contradict itself as a paradox: how could one conceive that which cannot be conceived? In the pre-Socratic spirit, the negation of something negates its own existence[2]. While it is possible to construct a word signifying a negation or an impossibility it does not mean that what is signified also exists, at least in the sense of being actual as opposed to fictional, predicative, or identificatory. So, to say that something was inconceivable to the human mind means that a now perceived as possible thought would not have occurred to the human mind before. However, within the world of computation the boundaries of impossibility are yet to be defined. The power of computation, which involves vast quantities of calculations, combinatorial analysis, randomness, or recursion, to name a few, point out to new thought

2.Parmenides said: ωςουκ εστι μηε ιναι = what is not, cannot be identifying a key separation between "what is" as a logical predicate and "what is" as a visual interpretation. See Popper, K., The World of Parmenides. London: Routledge, 1998, pp. 70–72.

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processes that may have not ever occurred to the human mind. These "idea generators" which are based on computational schemes have a profound ability not only to expand the limits of human imagination but also to point out the potential limitations of the human mind. What was inconceivable once may have been so mainly because it may have escaped the possibility of existence.

Similarly, the term impossible is used here to denote the incapability of having existence or of occurring. Yet, the boundaries beyond which possible starts to be perceived as impossible tend to change constantly in a world enhanced by computer-augmented human thinking. Even within the realm of the human mind those boundaries seems to expand in a Guinness-wise fashion. For instance, recently the total number of digits of the constant number Pi memorized by a human mind is 83,431, held in 2005 by a 59-year-old Japanese person named Akira Haraguchi. At the same time Japan wants to develop a supercomputer that can operate at 10 petaflops, or 10 quadrillion (10,000,000,000,000,000 or 1016) calculations per second, which is 35 times faster than the Blue Gene/L, the current US record holder with 280.6 teraflops – that is 280.6 trillion calculations a second, numbers thought to be astronomical a few years ago. Therefore, the boundaries of what is considered impossible may be shifting constantly based on real facts and not conjectures[3]. Where is the threshold beyond which something is impossible – or should we say the threshold below which something is possible? Theoretically, nothing is impossible. Even if it seems so at the moment, it may be that such a possibility has not yet arrived. The old proverb stated as "if you have all the time and all the resources in the world, is there anything you cannot do?" may indeed seem as a false premise yet it also defines the possibility of the impossible.

3. A set of graphs and tables that describe, assess, and project the potential of computers appears in the latest book of Ray Kurzweil. See Kurzweil, R., The Singularity is Near. New York: Viking, 2005.

Contrary to common belief, algorithms are not always based on a solution strategy conceived entirely in the mind of a human programmer. Many algorithms are simulations of the way natural processes work and as such they must not be regarded as human inventions but rather as human discoveries. Unlike inventions, discoveries are not conceived, owned, or controlled by the human mind, yet as abstract processes they can be codified to be exe¬cuted by a computer system. In this case, the human programmer serves the purpose of codifying a process, i.e. a translator of a process external to the human mind to be compiled into machine language which is also external to the human mind. For instance, a genetic algorithm is a process that simulates the behavior and adaptation of a population of candidate solutions over time as generations are created, tested, and selected

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through repetitive mating and mutation. The algorithm uses a stochastic search based on the chance that a best solution is possible and that computer processing power is effortless, rapid, and precise from the viewpoint of the human programmer. Yet, nothing in the entire algorithm is about human invention; the process is called natural selection (a process occurring in nature regardless of the presence of humans) and the flow of the calculations is logical or arithmetic (both processes occurring in nature regardless of the presence of humans).

Interestingly, algorithms can generate other algorithms; not only precise, identical, multiple copies of themselves but also structured text (i.e. code) that when executed will behave as an algorithm. In fact, the process of compos¬ing an algorithm is also an algorithm in itself, that is, the algorithm that created the algorithm. This self-referential property (which may be referred to here as meta-algorithm, i.e. the algorithm of an algorithm) is important in designfor at least two reasons: first, like algorithms, design can be seen as a set of procedures that lead stochastically towards the accomplishment of a goal. In studying the articulation of algorithms one may be able to discern similarities with design. While such a study may lead to the development of procedures that may be useful in design, more importantly, it may reveal certain clues about design as a mental process. This possibility opens up a more intricate relationship between design and algorithm that has been previously possible. Rather than using algorithms to copy, simulate, or replace manual methods of design (while perhaps desirable), instead they can be studied as methodologies that operate in ways similar, parallel, or complementary to that of the human mind. Second, along the lines of homo faber homo fabricatus (i.e. we make a tool and the tool makes us), algorithms can be seen as design tools that lead towards the production of novel concepts, ideas, or forms, which, in turn, have an effect in the way designers think thereafter. That way of thinking is incorporated in the next generation of tools that will, in turn, affect the next generation of designers, and so on.

It may be assumed that meta-algorithmics, that is, the creation of algorithms that generate other algorithms, is a human creation as well. A human programmer must have composed the first algorithm that, in turn, generates new algorithms and as such the initial programmer must be in control of the original idea. However, this is not necessarily true. Unlike humanly conceived ideas, where the author is the intellectual owner of the idea, algorithms are processes that define, describe, and implement a series of actions that in turn produce other actions. During the transfer of actions it is possible for a discrepancy to occur between the original intention and the actual result. If that happens

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then, by definition, the author of the algorithm is not in control of, and therefore does not own intellectually from that point on, the result¬ing process. Theoretically, ownership of an idea is intrin¬sically connected to the predictability of its outcome, that is, to its intellectual control. Therefore, in the absence of human control the ownership of the algorithmic process must be instead credited to the device that produced it, that is, to the computer.

Such a possibility, however, will be objected by those who believe that intellectual ownership can only be credited to an agent that possesses enough intelligence to be aware of its ownership, i.e. possesses consciousness. Unlike humans, computers are not aware of their environment. Perhaps then it may be necessary to define some other kind of awareness that may be only theoretical. This theoretical entity then would be the owner and the reason behind these intellectual phenomena until they possess a physical substance[4].

It is a common belief among architects and designers that the mental process of design is conceived, envisioned, and processed entirely in the human mind and that the computer is merely a tool for organization, productivity, or presentation. Whatever capabilities a computer may have it lacks any level of criticality and its visual effects are nothing but mindless connections to be interpreted by a human designer. It is a common belief that, at best, the computer can serve merely as a processor of information provided as data by the designer and as code by the programmer outputting simply the results of data processed by algorithms. What makes this process problematic is the fact that contrary to common belief algorithms can produce results for which there is no intention or prediction thereof of their behavior. Further, algorithms can also produce algorithms that also are not connected to the intentions or prediction of the original code. This structural behavior resembles in many ways Dadaist poetry, or Markov processes. In those cases, an algorithm functions as a string rewriting system that uses grammar-like rules to operate on strings of symbols in order to generate new strings of text. While the syntax of the resulting text may be consistent with the grammatical rules, the meaning of the resulting text is not necessarily associated semantically with the inten¬tions of the original code. For instance, the introduction of randomness in the arrangement of text can produce results that are unpredictable, but also accidentally meaningful. Unpredictability is, by definition, a disassociation of intention. But unlike chaos, a random rearrangement of elements within a rule-based system produces effects that, although unpredictable, are intrinsically con¬nected through the rules that govern that system.

4. The problem of ownership, jurisdiction, and responsibility of one human over another is perhaps best documented in the laws of slavery. If a slave makes a great discovery does it belong to the master, and vice versa if a slave makes a fatal mistake should the master be responsible instead?

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In the field of design, similarities may exist on formal, visual, or structural levels. Computational rearrangement of formal rules that describe, define, and formulate a certain style can produce a permutation of possible formal expressions for that style. For instance, drawing on Andrea Palladio's original 40-odd designs of villas, Hersey and Freedman[5] were able to detect, extract, and formulate rigorous geometric rules by which Palladio conceived these structures. Using a computational algorithm, they were able to create villa plans and facades that are stylistically indistinguishable from those of Palladio himself. In a similar, almost humorous fashion, the Dadaist engine is a computer algorithm that produces random text based on rearrangement of elements in a grammar. The resulting text, while based on random processes, is readable, often makes sense, and in some cases it is surprisingly intelligent. A version of this algorithm, called the "postmodernism generator," composes essays that appear as if they were developed by a human thinker. While in all of these cases it is quite apparent that awareness, consciousness, or intention is missing, the language patterns produced are convincing enough to lead some to believe that they were authentic, that is, worthy of trust, reliance, or belief, as if they were produced by a sentient author. In one case, a paper constructed using the Dada Engine software was allegedly almost submitted to a conference, which, had it happened, may have passed Turing's classic test of computer intelligence[6].

Unlike grammatical attempts to generate seemingly coherent thoughts based on linguistic patterns encapsulated through sentences, paragraphs, or essays, formalistic languages have already permeated the inspirational, conceptual, and critical aspects of architecture. Computer modeling software is being increasingly used by designers to produced form, shapes, or diagrams that while unaware of their logic are used as a means to address complex problems. Many architects and designers refer to their use of computers as intentional, their language for describing digital practice or formal phenomena has become part of the mainstream nomenclature, and, as a consequence, many so-called digital designs have even been publicized by critics as meaningful. In the last decade, architects have been using the computer as a device to generate, discuss, and critique new forms in an attempt to introduce a new way of thinking about design. While many have attributed the term "tool" to the computer because of its role as a device assisting during the design process, this assumption is not necessarily or entirely true[7]. Computational tools are based on algorithms, that is, processes written by programmers to utilize the arithmetic and logical capabilities of a computer in order to produce certain results. As with mathematicians, the invention or discovery of a mathematical formula does not necessitate the mathematician's knowledge of all the possible uses,

5. See Hershey, G. and R. Freedman, Possible Palladian Villas: (Plus a Few Instructively Impossible Ones). Cambridge: MIT Press, 1992.

6. The Turing test is a proposal for a test of a machine's capability to perform human-like conversation. Described by Alan Turing in the 1950 paper (Alan Turing, "Computing machinery and intelligence." Mind, vol. LIX, no. 236, October 1950, pp. 433–460), it proceeds as follows: a human judge engages in a natural lan¬guage conversation with two other parties, one a human and the other a machine; if the judge cannot reliably tell which is which, then the machine is said to pass the test. It is assumed that both the human and the machine try to appear human. In order to keep the test setting simple and universal (to explicitly test the linguistic capability of some machine), the conversation is usually limited to a text-only channel such as a teletype machine as Turing suggested.

7. Architects such as Neil Denari, Greg Lynn, or Peter Eisenman use the term tool to describe computational processes yet none of them has any formal education in computer science.

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repercussions, or consequences of the formula.

Similarly, it is possible that while a programmer has conceived an algorithm that will address a specific problem, the same algorithm might be used to address another completely different problem that was never predicted by the original author. Further, it is possible that using the same algorithm but utilizing different parameters than the ones that were originally designed, may result in a behavior that is completely unexpected. Consequently, when a designer uses an algorithm to design, the designer may not be aware, knowledgeable, or conscious of the mechanisms, specifications, or repercussions of the programmer's algorithm. The gap of discrepancy that separates the programmer from the designer is indeed problematic mainly because of the nature of algorithms. Unlike physical tools where unpredictability is of a mechanical or chemical nature, algorithmic tools are abstract, rational, and intellectual in nature and therefore related to the human mind. So, in that context, the output of an algorithm must be associated to a human mind, either the programmer or the designer. Anything else would be absurd because it would involve an intellectual process without the pres¬ence of a human mind. Therefore, critique on the output of an algorithm must be associated to the designer who creatively used the algorithm or to the programmer that made the algorithm available to the designer. In other words, it always has to be a human being responsible for anything that resembles intellectual behavior. However, if someone abandons the humanistic premise and introduces an intellectual entity that, while not identical, nevertheless resembles the human mind, then a different interpretation of design might be possible. Under such a possibility, the human mind is enhanced, complemented, or synergized with an intellectual entity of a computational nature, independent of a human presence, which we will call here otherness, or, in Greek, allo. The reason for the existence of such an entity and its disconnection to the human mind is due the unpredictable, inconceivable, and impossible nature of its origin. In other words, its existence starts where the human mind fails. Consequently, any intelligent behavior by this entity is not a matter of chance, accident, or disguise but rather the output of an allo-logic whose complexity is beyond human comprehension. Armed with such allo-reasoning the human mind can be described as a cyborg, not in the mechanical or electrical sense, but in that of an intellectual one.

While the computer is a device conceived, designed, and built by humans, the processes running within its circuits are not necessarily a human invention as well. Like mathematics or geometry, computation is not an invention but rather a discovery. It is not necessary for a human being to exist in order for computational processes to occur. In other words, computation is

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of an independent nature and can be implemented on various devices including the computer or, to some extent, the human brain. Otherness is that part of computation that would be described by humans as inconceivable, impossible, unpredictable, or unbelievable, not as linguistic terms but as undiscovered concepts. And yet the possibility that something may exist beyond the comprehensible defines the notion of otherness, that is, of something else. While the human mind has the ability to combine events from the past in order to predict their possibility of existence in the future, otherness is about those possibilities that were missed, overlooked, considered impossible and therefore omitted, or those whose chance of probability were too far into the future or lost into the oblivious past[8]. In any case, their chance to exist is being brought to life by devices that have the ability to perform calculations far more complicated than any human brain or brains together can. However, it is important to mention here that certain tasks or events observed in nature are indeed impossible, yet they are not intellectual. In contrast, impossible tasks related to human thinking are by definition intellectual and, as such, challenge not only the intellectual nature of the human mind but also its own existence.

For the last five decades, beginning with early CAD programs and continuing through high-end computer graphics, modeling, and animation systems, architects have been increasingly concerned with the possible loss of control over their own designs due to the powerful yet complicated, if not mysterious, nature of computers. This concern has led them to position themselves within a wide spectrum of speculations about the effect of computers on design that ranges from complete rejection, elitism, or demonization of their use as design generators to the complete antithesis, that of adoration, worship, or popularization of their use. When comparing avid computer users to those reluctant to engage with them it is necessary to overlook many significant and distinguishing differences in order to identify at least one common theme: the assessment that there is something different, unprecedented, and extraordinary about the computer as it compares to traditional manual tools.

Both non-users and users agree that the effect computers will have on design whether desirable or not will be significant, profound, and far-reaching. This agreement is based on an important yet peculiar relationship between design and its tools. It is apparent that design is strongly dependent on the tools utilized and, reversely, tools have a profound effect in design[9]. Traditionally, this dependency is controlled by the human designers who decide which tool is to be used when and where as well as the range of possibilities a tool has for addressing, resolving, or accomplishing a design task. Further, it is possible that the use of

8. Marcos Novak points out that while the clause “if-then” is a syllogistic structure that leads on to new knowledge, the clause “if-then-else” involves the alternative “else” that may point to the opposite of knowledge, that is, to “that which does not follow from its roots, or, indeed, that whose roots can no longer be traced, or have become irrelevant, or are unknown, or follow from principles outside previous understanding.” See Novak. M., “Alien space: the shock of the view,” article reproduced from Art + Technology Supplement of CIRCA 90, pp. s12–13.

9. In the words of Marshall McLuhan “first we build the tools, then they build us.” Perhaps, Stanley Kubrick and Arthur Clark’s movie “2001: Space Odyssey” is a good fictional example of this possibility.

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have further implications in the process of addressing a task: just because a tool is available, a task is now possible, or, further, a tool implies a task. However, a problem arises when the tool is not entirely under the control of its user. In the case of a computer as a tool, the results may be unexpected, surprising, or unpredictable even by the users themselves. While such moments of surprise may be advantageous, enlightening, or perhaps even undesirable, they do exhibit a theoretical interest because they challenge the basic premise of what a tool is or how a tool should behave. Further, such behavior may lead to alternative ways of executing the task that were not intended and may lead to results often superior than intended. Such a possibility in turn challenges one of design's most existential qualities, that of intention. Is intention necessary in design? Is intention a human privilege only?

Intention is a term used often in the context of consciousness. The definition of intention is associated with a plan on action, a determination to act in a certain way, a thoughtful and deliberate goal-directedness. In all cases, intention is attributed (at the absence of any other source) to the human mind as the source of intention. Further, intention is also associated with design, because design is traditionally considered an act of conscious decision-making with an intention in mind. The problem with this approach is that it assumes that behind every decision a conscious mind must be present. However, if we disassociate the act of decision-making from the involvement of a conscious plan, if we simply accept that decisions can be made by unconscious agents, then a more intricate relationship between decision and intention emerges than has been previously possible. Rather than confining the act of deciding within the human domain a more loose interpretation of decision-making can be established that includes other decision agents not necessarily human. In such a context, the notion of intention does not have to be associated with its source but rather with the process itself. For instance, a design decision may be made by an algorithmic process not intended by the designer, yet as the result on the decision may have been assessed as "successful" the designer may adopt it as one's own idea. In this case, intention was assigned after the fact. While such action is impossible within a humanist world, it is so only in the absence of anything else. Because, if a human is not responsible for an intention then who is?

In response to a possible shift away from the traditional view that the human mind is the central point of reference for any intellectual activity, two theories have been dominant; either a self-referential reconfirmation of the uniqueness of the human

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mind as the only conscious, sentient, and intelligent system that exists or an acknowledgement that the quantitative limitations of the human mind and the superior computational power of the computer are indications that the human mind is not as central and unique as previously thought. Humanistic approaches to new knowledge have traditionally stressed the importance of self-determination and rejected any dependency on supernatural, mystical, or magical phenomena. It doing so they endorse the ability of humans to rationally determine, evaluate, and justify their actions. Implicit, however, in this determination is the assumption that humans must be in control and therefore be reliable for their thoughts, morality, and actions and not rely on supernatural means. The notion of control is therefore central to the humanistic position. Nonetheless, while the notion of predictability (and consequently responsibility) is typically linked to human control, its negation implies the presence of a supernatural alien realm. Such an alien realm can be unveiled through inductive algorithms since such processes embed an equivocal ability to connect logical patterns with electronic patterns. In the field of design, the notion of unpredictability challenges one of its traditional modes of thought where typically the designer is in full control of the tangible or virtual representation of one's design ideas.

Designers and architects have traditionally maintained control over their design work by employing explanatory, analytical, generative, or representational ideas directly linked to the principles of human understanding and interpretation. Of course, any human-centric approach is associated by definition with subjective phenomena and personal interpretations. Within that realm, any logic that deals with the evaluation or production of form must be, by default, both understandable and open to interpretation and criticism. The problem with this approach is that it does not allow thoughts to transcend beyond the sphere of human understanding. In fact, while it praises and celebrates the uniqueness and complexity of the human mind, it becomes also resistant to theories that point out the potential limitations of the human mind[10].

10. Strange as it may sound, acknowledging lack of control is, in a way, more human than rejecting it. Humanism is not about rejecting anything that threatens human control but rather about accepting limitations and working towards solutions.

Intellectual property is defined as the ownership of ideas and control over the tangible or virtual representation of those ideas. Traditionally, designers maintain full intellectual property over their designs or manifestations thereof, based on the assumption that they own and control their ideas. This is not always the case with algorithmic forms. While the hints, clues, or suggestions for an algorithm may be the intellectual property of the designer–programmer, the resulting tangible or virtual representations of those ideas is not necessarily under the control of their author. Algorithms employ randomness, probability, or complexity the

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outcome of which is unknown, unpredictable, and unimaginable. If there is an intellectual root to these processes it must be sought in a world that extends beyond human understanding[11]. Both the notions of "unknown" and "unimaginable" escape from human understanding since both negate two of the last resorts of human intellect, that of knowledge and imagination. An algorithm is not about perception or interpretation but rather about exploration, codification, and extension of the human mind. Both the algorithmic input and the computer's output are inseparable within a computational system of complementary sources. In this sense, synergy becomes the keyword as an embodiment of a process obtainable through the logic of mutual contributions: that of the human mind and that of the machine's extendibility.

There are often misconceptions about the computer as a machine (i.e. a box with electrical and mechanical interconnections) and its role in the process of design. Design, like many other mental processes, at the information-processing level has nothing specifically "neural" about it. The functional equivalence between brains and computers does not imply any structural equivalence at an anatomical level (e.g. equivalence of neurons with circuits). Theories of information processes are not equivalent to theories of neural or electronic mechanisms for information processing[12]. Even though, physically, computers may appear to be a set of mindless connections, at the information level they are only a means of channeling mathematical and logical procedures[13]. However, there is indeed a fundamental difference between the quantitative nature of computation and the abstract holistic nature of human thinking.

Is design thought quantifiable? In response to this question, two options appear to be possible; either that design is a process based upon finite elementary units, such as bits, memes, nodes, atoms, etc. or that it is a holistic process with no beginning, end, or any in-between measurable steps. The negation of discreteness implies a continuity of thought that permeates throughout the process of design but is confined within the boundaries of human domain. By definition, subjectivity depends on interpretation and only humans are in a position to do so (yet). Certain intellectual activities, such as intuition, interpre-tation, choice, or meaning are considered human qualities that can hardly be quantified, if ever. In contrast, the discretization of design opens up a multitude of possibilities as it invites discrete mathematics to be involved in the design process, such as logic, set theory, number theory, combinatorics, graph theory, and probability.

Discretization of design by definition can be addressed, described, and codified using discrete processes executed today by discrete numerical machines (i.e. computers). However, the

11. Sir Karl Popper argued that the world as a whole consists of three interconnected worlds. World One, is the world of physical objects and their properties–with their energies, forces, and motions. World Two is the subjective world of states of conscious¬ness, or of mental states – with intentions, feelings, thoughts, dreams, memories, and so on, in individual minds. World Three is the world of objective contents of thought, especially of scientific and poetic thoughts and of works of art. World Three is a human product, a human creation, which creates in its turn theoretical systems with their own domains of autonomy. See Popper, K. R., The Logic of Scientific Discovery. New York: Harper & Row, 1968.

12. The works of Herbert Simon and Allen Newel in the 1960s and 1970s are undoubtedly some of the best examples of the study of artificial intelligence.

13. Greg Lynn, in Animate Form. New York: Princeton Architectural Press, 1999, p. 19, describes machine intelligence "as that of mindless connections."

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problem is that discrete/quantitative design provokes a fear of rationalistic determinism that is long considered to be a restraint to the designer's imagination and freedom[14]. Such resistances have attempted to discredit Computer-Aided Design (CAD) products or processes as inadequate, irrelevant, or naïve. According to one position, design is considered a high-level intellectual endeavor constructed through uniquely human strategies, i.e. intuition, choice, or interpretation. Such theoretical design models negate computation as a possible means for design realization mainly because it is based on discrete processes that are finite and, as such, restrictive.

14. Colin Rowe's criticism on Alexander's Notes on the Synthesis of Form and consequently extending it to all value-free empirical facts is that they are only "attempts to avoid any imputation of prejudice." See p. 78 in Rowe, C. and F. Koetter, "Collage city", in Architectural Review 158, no. 942, August 1975, pp. 66–90.

In contrast, human thought appears to be continuous, infinite, and holistic. However, in practice neither case alone seems adequate enough to serve as a concrete model for design because both suffer from a lack of autonomy. Human designers fail to compute extreme quantitative complexity and computational processes fail to justify consciously even simple decisions. However, these disjunctions result from a logic that seeks to compare two separate, disjoint, and unconnected processes, neither of which has any effect on the other. While traditional human strategies have a long history of success in design, computational strategies are not exclusive, divisive, or restrictive, but rather alien, foreign, different, and, as such, incomparable. Rather than investing in arrested conflicts, both strategies might be better exploited by combining both. What is considered smart in the one world may be considered naïve in the other and vice versa, but by combining both, a strategy can always be available.

For example, any painting can be represented as a finite grid of finite colors. The exhaustion of all possible combinations of all possible colors within the grid of pixels eventually will reproduce any painting that was ever created in the history of humanity and, as a consequence, any painting yet to be created. Formally, such an argument can be written in the following way:

$$P = \{(x, y, c)\ x, y, c \in N, 0 \leq x < w, 0 \leq y < h, 0 \leq c < d\}$$

where $w = 132$, $h = 193$, and $d = 2$. In this case, the possible combinations are $2^{(132 \times 193)} = 10^{7669}$.

While the possibility of creating a specific painting, i.e. Matisse's Icarus[15], from a random arrangement of colors may appear to be "almost impossible" it is indeed not so; specifically it lies somewhere between 1 and about 10^{7669} possibilities. If there is a possibility, whatever remote it may be, there must be a chance that it will occur. While the human mind may be bounded to the limitations of quantitative complexity, its computational exten

15. Icarus, the son of Daedalus (creator of the Labyrinth), is a metaphor for an impossible task, consequent failure, yet eternal remembrance. Of course, any bitmap image of those dimensions would require the same number of calculations.

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sion, the computer, allows those boundaries to be surpassed. The notion of "impossible" is no more the assessment of human imagination but rather a degree of probability[16].

In contrast to this example, assessing the notion of possible can be enhanced by another model. This model is based on the idea that, in search of a known target, not all possibilities are equal. Certain possibilities may have a higher chance of success than others. This possibility of possibility opens up a more intricate relationship than has been previously possible. Rather than simply enumerating all possible patterns in search for a known one, genetic algorithms assess each random step. By assessing the degree of promise that a certain pattern has the notion of selection is introduced in the decision-making process. The selection starts from a population of completely random patterns and occurs in steps (i.e. gener-ations). In each step, the fitness of the whole set of patterns is evaluated, multiple patterns are stochastically selected from the current population (based on their fitness), modified (mutated or recombined) to form a new pattern, which becomes current in the next step of the algorithm. For example, using the previous example, instead of assuming that each random pattern is equal in importance and therefore going through all of them until a perfect match is found, a preferential selection may occur instead. The number of iterations in the case of Icarus will be reduced quite significantly from 10^{7669} to merely 3,280,000 (i.e. 3.28×10^6).

Randomness is often associated with lack of control, arbitrariness, and incoherence but more importantly the possibility of a random occurrence in essentially dependent on time. Possibility is the state occurring within the limits of ability, capacity, or realization in response to both time and resources. So, the question arises as to whether there is anything that cannot be done if one has infinite time and infinite resources? If anything is possible, then isn't merely thinking of something in itself its own definition of being? Information, the root of knowledge, is derived from the prefix in-and the noun formation. In its linguistic context, information means giving form, figure, shape, and therefore organizational structure to, apparently, formless, figureless, and shapeless notions. Information should be understood not as a pas¬sive enumeration of data but rather as an active process of filtering data, not in the trivial sense of awareness, but in the strict sense of logical proof. While the quantity and composition of external data may appear to be infinite, random, or incoherent logical filtering will lead progressively to an ordered formation. Unlike blind randomness, certain algorithms (i.e. genetic) are capable of selectively controlling the shaping of information. Such algorithmic events result from factors that are neither arbitrary nor

16. A single processor working 1000 GIPS can only perform 10^{18} operations in a year. So, if 10^{400} computers will work in parallel (because the problem is not sequential), they will be finished in a year; or 10^{800} computers in half a year. In other words, 10^{7K} is indeed an impossible number for us but not necessarily so for a network of computers.

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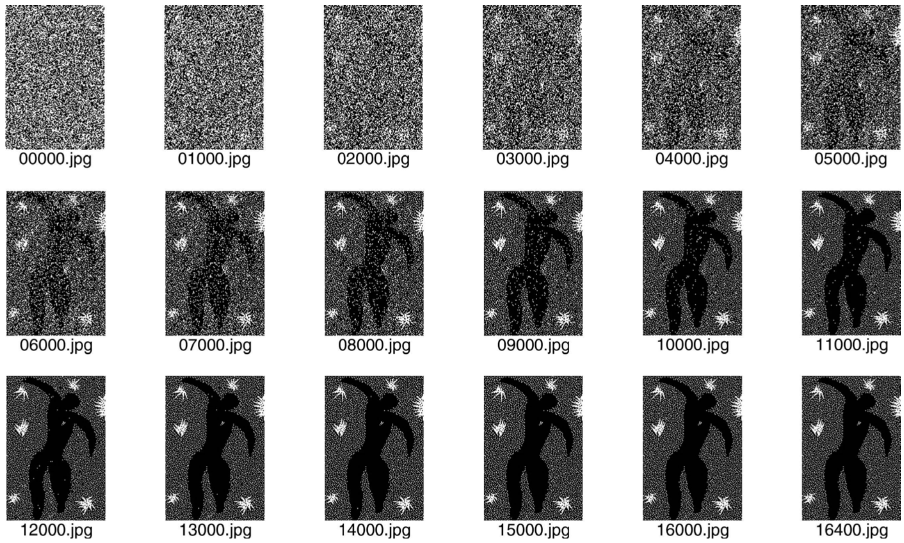

Figure 1.
The phases of a genetic algorithm that seeks to produce an image

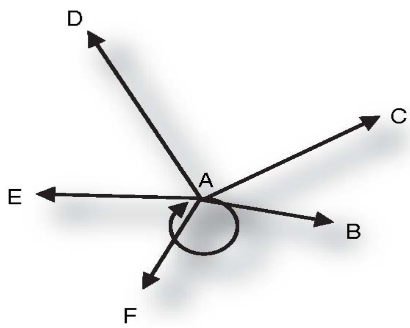

Figure 2.
The relationship between one and another is not the same as with one and itself

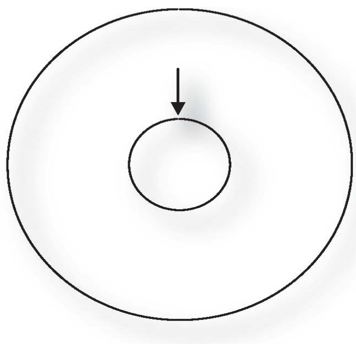

Figure 3.
Observing a system from outside still lies inside another system

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predictable yet seem to be guided by some sort of intelligence. While these events are made possible by simulating natural processes without involving human intelligence, yet it is inevitable to assume that some human intelligence is involved in the selection of the natural process that best fits the problem of randomness. Human intelligence arises as an act of preference.

Preference is the grant of favor or advantage to one over another. It is a subjective formation of an idea that leads eventually to choice. As subjective actions are dictated by one's own criteria, a problem arises when such actions refer back to the same person. For instance, an architect, in designing a house for a client, is trained to observe, detect, and address certain preferences of the client. Yet, when the client and the architect are one and the same person, then preferences tend to elude one's own mind. This happens either because one is not able to comprehend fully one's own mind or because one may miss certain aspects. "While one knows what one knows, one certainly does not know what one does not know." This seemingly self-evident statement is not so, in at least two ways. First, the assertion that one is unaware of one's own ignorance is impossible within the sphere of that person's knowledge; for if it were true then one would know what one does not know, which is an apparent contradiction. Second, the fact that the statement is in quotes means that it is being stated by a third person in which case the lack of knowledge of ignorance may be viewed as such from the third person's viewpoint. In other words, only a third person may be able to detect the incompleteness of another person's knowledge.

In mythology, Ulysses introduced himself to the Cyclop as "nobody." Later on, when the Cyclop was looking for help nobody would help him because nobody hurt him. This last statement is self-consistent within its own linguistic context but not if one gets out of the context and assigns the name "nobody" to somebody. Then the whole statement has a different meaning, yet undetected for those inside the system. Godel's incompleteness theorem claims that within any consistent formalization of a quantifiable system a statement can be constructed that can be neither proved nor disproved within that system. The beauty of Godel's argument is not only in pointing out a discrepancy in reasoning but, most importantly, in revealing the existence of an alien realm that bounds the known universe.

Allo can be defined as a representation of something else, not in the sense of a metaphor, but in the realistic sense of referring to something unknown and therefore evasive, whose entrance point, gateway, or portal can be glanced through by negating reason and venturing instead on alternative paths. Allo is by defini-

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tion a-logical as it. arises when the if-then clause fails. Yet, while it is not illogical, devoid of logic, or senseless, it represents those possibilities that are out of the bounds to which the first logic can apply. Allo is not human; it is a human discovery that helps describe, explain, and predict lack of knowledge. It demarcates the end of human reasoning. It is the opposite of "is"; allo is everything else.

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Low-Tech Geodesic Gridshell: Almond Pavilion

Enrique Soriano // Barcelona Tech, UPC

Abstract

Traditional timber gridshells are extremely efficient but the required calculation experience and erection complexity make them neither appealing for the industry nor accessible. This paper shows the research in progress conducted on the universalization of alternative irregular gridshells based on geodesic patterns. The paper defines geodesic gridshells and discusses their suitability for scarce budgets and low-tech manufacturing of free-form shells. We introduce the research motivation, the historical framework, the geometrical properties of geodesic curves, and their structural corresponding advantages. We expose then our geodesic pattern design method on a free-form surface, obtaining a simple layout for the manufacturing of a multilayered gridshell. Finally, we discuss the benefits and challenges based on the experience from testing the concept with a built low-tech elastically-bent green timber gridshell.

Keywords

Geodesic gridshell, timber gridshell, low-tech fabrication.

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Introduction

In recent years the blossoming of computational tools in design has led both to the emergence of free-form architecture and to a very interesting field of architectural geometry enabling its conception, optimization, rationalization and fabrication. These optimized symbiosis of form and manufacturing, although very efficient, often requires of exclusionary multiaxial numerical control, not always accessible. This paper is concerned with the manufacturing by not only efficient but also universal means of efficient forms namely thin shells. We define universalization as the accessibility of efficiency: investing the effort in design rationalization while keeping a low advanced machining dependency.

Shells are structures defined by a curved surface and often a doubly curved surface and by being very thin in the perpendicular direction to the surface (Naicu et al., 2014). Shells use the minimum amount of material to carry imposed loads using primarily membrane action, gaining strength through form rather than mass (Chilton and Tang, 2017). Nevertheless, it has the problematic of curved and often bespoke manufacturing. In this sense, gridshells defined as structures "with the shape and strength of a double-curvature shell, but made of a grid instead of a solid surface" (Douthe et al., 2006) are a solution by concentrating the structure into its strips (Johnson, 2017). These strips or laths can describe the gridshells in two groups (Naicuet al., 2014): from node to node or with long elements spanning across the structure, defined as continuous grid members. The traditional elastic gridshells are included in this latter group of long continuous beams, and ground its form in the elastic deformation of a flat deployable regular grid mat. Despite its benefits (large spans at small material, transport and assembly cost), elastic gridshells have been undermined by the cost and complexity of their erection method from its inception in the late 1960's (Quinn et al.,2014).

Alternatively to elastic gridshells, ribbed gridshells arouse by the same period under the lead of Julius Natterer as a "rational development of the original Frei Otto foldable lattice shell" (Chilton and Tang, 2017). Both elastic gridshells and ribbed gridshells ground their manufacturing in the principles of active bending in a geometric based approach (Lienhard et al., 2013), by exploiting the material properties and the cost-efficiency of obtaining form by means of elastic deformation, with the difference that the ribbed gridshell "was constructed directly onto the final profile on temporary supports rather than being assembled flat and coaxed into the double-curved form" (Chilton and Tang, 2017). But above all, ribbed gridshells were different in the "use of thinner and wider boards" for the laths, "more easily bent to a curved profile and less likely to break during bending" (Chilton and Tang, 2017). In order to reduce unfavorable stresses, the geometry of laths is restricted to follow geodesic curves in a surface in order to simply twist and bend along the weak axis.

From this pioneering strategy, a large collection of research and built examples exploited the geodesic curves as an efficient method for assessing the construction or cladding of free-form shells. This paper is concerned with the gridshells in which network of curves are intentionally following geodesic curves in a surface, and that we can define as geodesic gridshells.

Background

2.1 Geodesic network

A geodesic line on a surface is defined as a locally distance minimizing curve, where the normal vector of both curve and surface are parallel or antiparallel at each point (Pirazzi et

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al., 2006), this is, the second derivative to any point of a geodesic lies along the normal to a surface at that point (figure 1.c). We can imagine them as the paths a non-steering vehicle would follow at constant velocity (no acceleration) on a landscape: geodesics preserve a direction on a surface. Otherwise said, geodesic curves in surfaces are the curves of zero geodesic (sideways) curvature (Pottman et al., 2010) although they have normal curvature and torsion.

These geometrical properties produce very useful constructive contingencies :

- Geodesics, also called plank lines, can be built out of inexpensive flat and straight boards where bending in the strong axis, is avoided, and are subjected only to bending about their weak axis and to torsion (Pirazzi, 2006). Inversely, "straight strips, ribbons, are geodesic lines that roll out "autoparallel" on a surface" (Lind, 2007) (figure 1).
- When two geodesic curves cross, they both share their the normal vector at the intersection point, thus the joint can be built with a simple inexpensive rotational joint. On the unrolled rectangular flat stripe, the location of the intersection is directly taken from the distance along the geodesic, and can be manufactured by simple universal means (figure 2).

Geodesic gridshells are the network of at least two intersecting discrete families of geodesics, and their convenient properties spread across the surface. A geodesic net (Lind, 2007) is the built non-orthogonal and non-conformal coordinate system of geodesic lines describing a curved surface. Assembling "thin and long material-strip elements to follow the coordinate lines" form a curved mesh structure (Lind, 2007) namely a geodesic gridshell. Furthermore, geodesic gridshells can be specially interesting as supporting structure of a curved shell (Pottman et al., 2010). First, geodesic networks can be orientated and spaced intentionally. Second, geodesics are "the equilibrium shapes of elastic curves constrained to the surface" (Pottman et al., 2010). Third, the complexity of the manufacturing of a bespoke curvature is simply concentrated in the specific location of the joints, and the curvature emerges directly by the assembly of deformed planks.

2.2 Geodesic gridshells

Traditionally, the empirical taming of the elastic behaviour of some materials has allowed the manufacturing of thin shells (Liendhard et al., 2013). In some types of basketry, wide pliable strips are empirically bent and braided. "Since the material-strip element's width greatly exceeds their thickness, the introduction of geodesic curvature k_g is prevented"(Lind, 2007). The paths of the strips can then be assimilated to geodesic curves and somehow the grid of basket strips is describing a surface by a geodesic net. Similarly, in ancient shipbuilding the use of geodesics have been underlying in the iterative plank attachment to the master frame.

Nevertheless, an intended use of the geodesic paths was already established by Sir Barnes Wallis: "enlarge the internal skeletal structure to full streamline dimensions, by forming its members as geodesics in the surface of both wings and fuselage, thus getting a much lighter, stiffer and stronger structure than ever before". The pioneering design, first applied in airships in 1920's and then in airplane designs in 1930's, was providing a solution to the manufacturing of complex streamlined surfaces: By having the geodesic curves form two helices at right angles to one another, the members became mutually supporting in a manner that the torsional load on each cancels out that on the other (www.barneswallisfoundation.com, 2017).

Decades later the IBOIS-EPFL lead by J.Natterer developed a new kind of shell structure by the name of ribbed shells in which simple planks following geodesic curves were creating a network of ribs. Layers of laths were waved together, completely filled in between and screwed (Natterer et al., 2008) The first application was the Polydôme in the early 90's: a spherical dome was created by laying the planks in a diagonal pattern (segments of great circles) over temporary supports (Chil-

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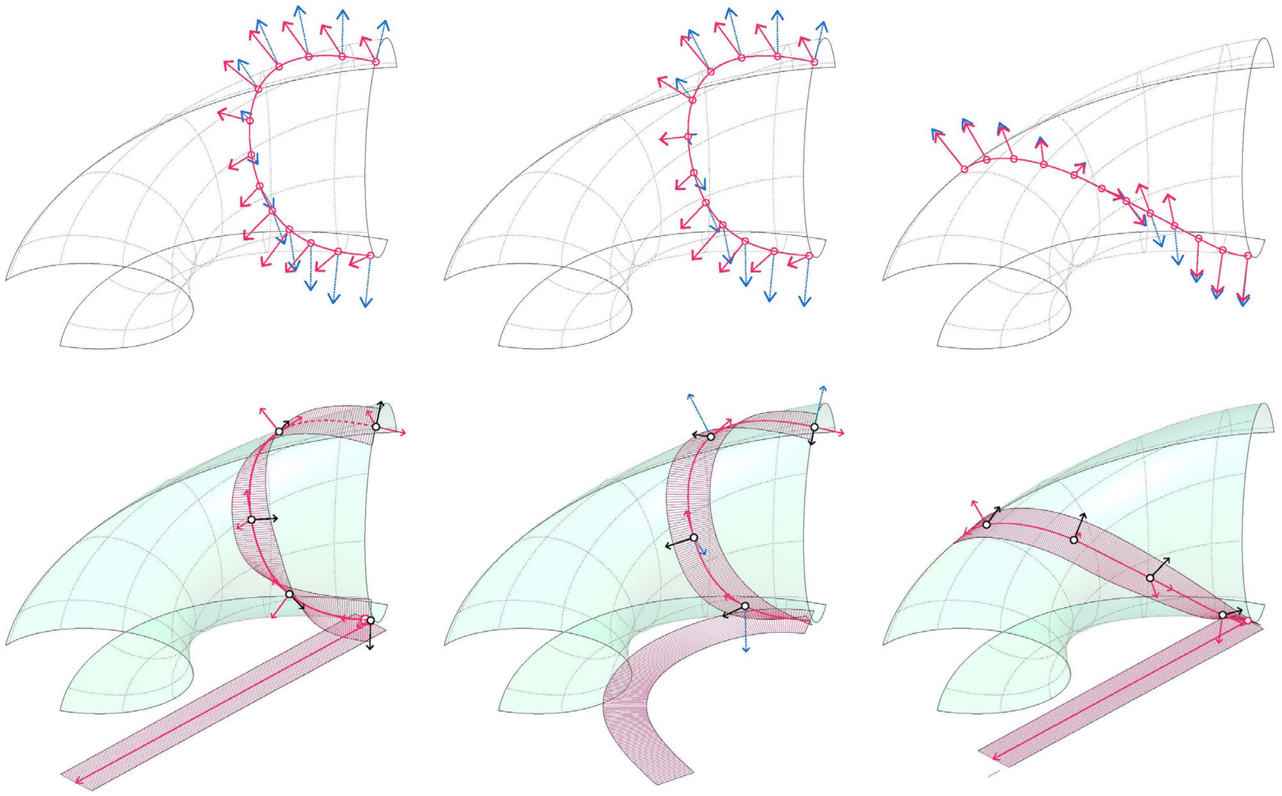

a b c

Figure 1.

Curves on surface (top: surface normal in blue, curve normals in magenta; bottom: unrolling of developable surfaces lying on the curve and tangent to the binormal vector in black) a. Arbitrary curve: free twisting stripe not tangent to surface unrolls straight b. Arbitrary curve and developable surface with imposed surface normal: stripe unrolls in curved trajectory. c. Geodesic curve: stripe is tangent to the surface and unrolls straight.

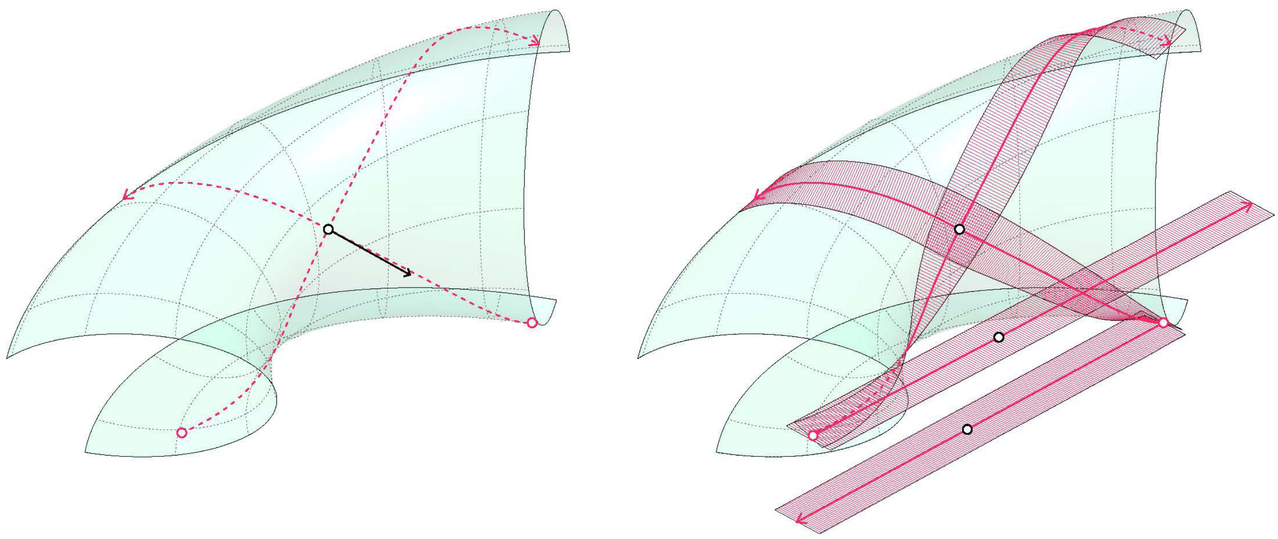

Figure 2.

a. Two geodesic curves intersecting.

b. the unrolling of the developable surfaces lying on the geodesics, and the intersection point marked on both

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tong and Tang, 2017) (figure 3.a). One of the benefits of designing an irregular grid is the intentional variability of the rib spacing, concentrating density where loads flow. The successful strategy was used in several projects, varying surface definition and grid parameters until the very ambitious project Expodach in Hannover, where the two geodesic pattern had the additional constraint of intersecting orthogonally (figure 3.b) in a minimal surface. The complete roof thin shell is discretized in prefabricated modules. More recently Toyo Ito architects have implemented the same structural technique for a large roof, with the particularity of having three families of geodesics flowing along a continuous surface.

Many alternative and experimental systems appeared during this period, exploring free-form surfaces, or expanding the grid. The Kupla gridshell (2002) was the outcome of an intuitive approach to geodesics: curves were digitally reconstructed based on the behaviour of small laths on physical models of complete free-form surface. The final construction consisted in the assembly of squared 60x60mm battens “bent and twisted on-site from seven pre-bent profiles” (Chiltong and Tang, 2017) (figure 4.a). In a larger scale, the Waitomo gridshell (2010) takes advantage of the prefabrication of individual elements by cleverly imposing a regular grid of spiraling geodesics on a regular elliptic torus: a single twisting curve is needed for the anticlastic surface. Then, prefabricated twisting 160x36mm LVL laths were assembled on site and clamped together with shear blocks already glued in the lower chord (figure 4.b). However, methods for the design of geodesic patterns on free-form surfaces, were presented (Kensek et al., 2000), and successfully tested (Pirazzi et al., 2006) by simple elastic deformation with very thin laths, which simplifies and universalizes the technology. It is argued that the extra cost of manual labor in the assembly is compensated with the rationalization of planning and manufacturing (Pirazzi et al., 2006). This research triggered our curiosity to test the concept in a larger scale with limited resources.

Design Proccess

In the parametric modelling environment Grasshopper, we adopt a similar process as shown in (Pirazzi et al., 2006), although we include the construction system and the material properties as constraints for defining the surface.

The first part consists in the form definition, taking as extrinsic input (fixed) the boundary conditions which are curves and the material properties (thickness, length of boards, splice length), and as intrinsic inputs (editable) the starting grid parameters, and an arbitrary curve control points. The first step builds an adjustable nurbs surface with the input curves which will be midway of the layers of the gridshell. The next step is the generation of the geodesic network over the surface: the density is controlled by n evenly spaced starting points on boundary curves and the grid angle aspect is controlled by the shift of corresponding points in the next curve. For the calculation of the geodesic we make use of the native algorithm inside Grasshopper, which minimizes the length of a curve between two points on a surface. The generated geodesics will lay on the virtual mid surface and will be the only which won’t be built, but serve as guide.

Regular grids on double curvature surfaces trims the borders which needs to be collected by perimetral beams, whereas in this case the grid starts conveniently from defined supports but the grid spacing is uncontrolled if not prevented with evenly spaced geodesics (Pottman et al., 2010) tending to widen in the convex areas (Pirazzi et al., 2006). Given the material properties, the final step validates the network by verifying the normal curvature of the geodesic paths: for thin boards “the width has no influence on the bending stress which can therefore be expressed proportional to the thickness t and curvature” (Liendhard et al., 2011).

The second part is the process of fabrication rationalization and documentation, which takes into

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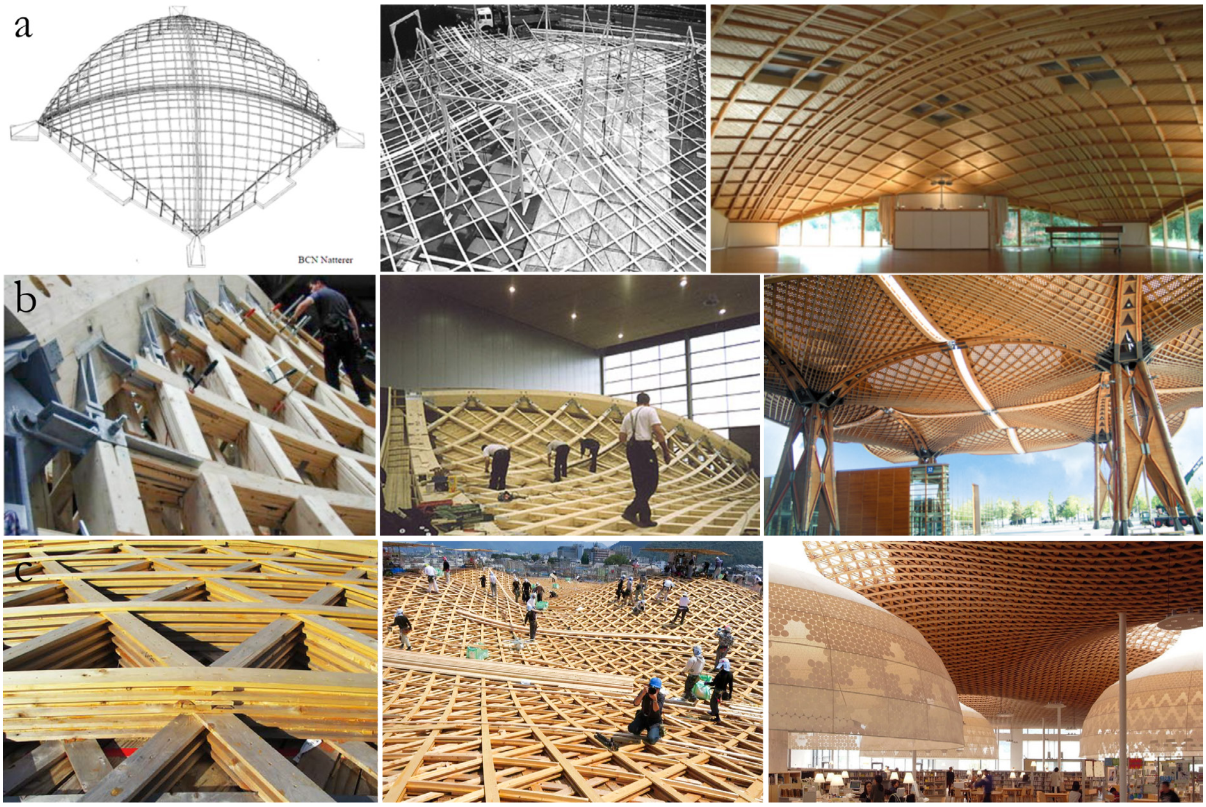

Figure 3.
Ribbed shells a.Polydôme (1993) b.Expodach (2000) c. Mina-no-mori (2015)

Figure 4.
Assembly of individual pre-bent geodesic laths. a.Kupla observation tower(2002). b.Waitomo Caves

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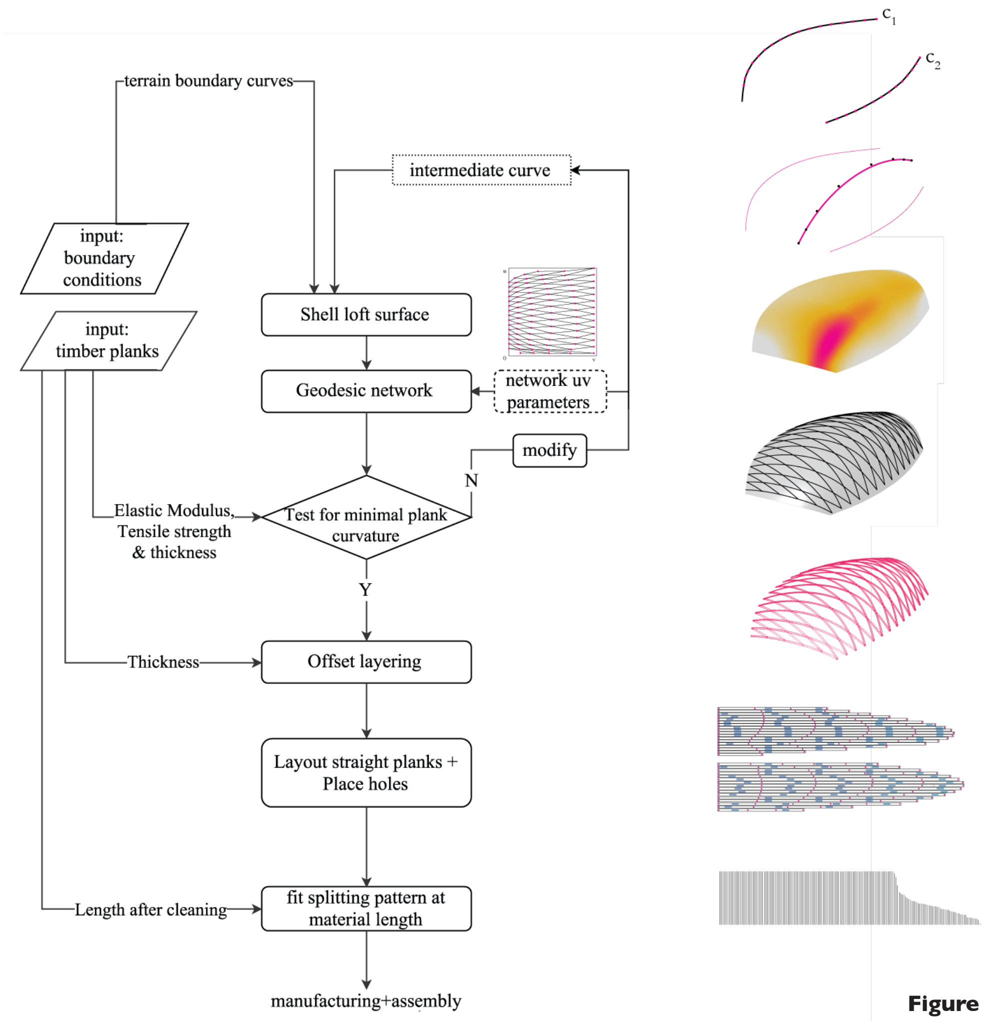

Figure 5.
Form defining process and procedural documentation

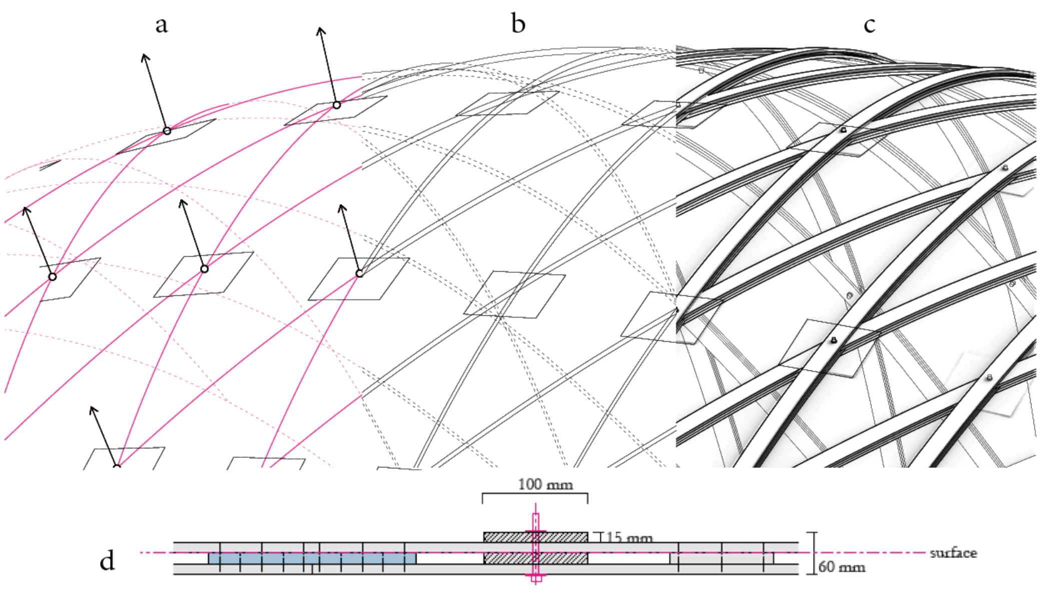

Figure 6.
a.Geodesic curves over neutral fiber surface and surface normal vector at their intersection
b.Geodesic offset curves c.Visualization of layering. d.Composition of layers and splicing.

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account the materiality of the construction system. The first step is simply extrapolating the geodesics on the surface normal according to the board thickness and number of layers, and although these curves won't be exact geodesics of the "enveloping surface to which they belong" the inaccuracy seems negligible (Pirazzi et al., 2006). Next, the planks are laid by taking the geodesic curve lengths and redrawing straight lines of the same length. The intersection loci of the network provides the distances to place the joints on the straight lines. Finally a custom algorithm locates the splicing joint avoiding the overlap with the node joint, while maximizing the number of standard lengths of planks.

Implementation

At the end of 2012, the ETSAV architecture school organized a landscape competition. As we (the CODA team) were eager to build more timber gridshells, we proposed a multipurpose geodesic gridshell which would be supported by the Catalan Institute of Wood, which happened to be the office next door. Despite losing the competition, we still presented the feasibility of the idea and availability of material, and seduced the academic community. After some months, in a bright and cold weekend, we converted the cantine terrace into a plank manufacturing facility, and we transformed the 1,5 m3 of freshly sawn green timber fitting in a van into a gridshell.

Varying the external inputs, the same parametric model was used for the competition model and the final construction. The surveying of the curved boundary conditions consisted in the photogrammetric reconstruction of two elastically bent plywood battens, placed on the site hill, which were then manually rebuilt in CAD. Supports allowed free rotation in the normal and tangent plane of the planks but no twist was allowed. The surface was designed in order to reduce curvature in the boundaries. The supports were made out of corrugated bar and twisted plates.

In order to promote the use of local timber, the sponsor provided the widespread pinus halepensis, even though it's normally used for non-structural uses and we asked to be green in order to facilitate the assembly. The boards arrived in rough sections of 100 x 15 mm with a large variation of grain and lengths. Once the planks were sorted by grain quality, leaving the denser and cleaner grains for structural use, they were cut in specific length, and spliced with overlapping pieces of reclaimed shortened planks. The reduced size of the shell, and the fibrous nature of timber provided enough tolerance to absorb the possible small errors due to the manual process of measuring and boring of the assembled planks, and no piece nor hole needed to be repeated (Figure 6). Interestingly the complexity of a doubly curved shell could be solved with a one-dimensional drilling tool.

The assembly consisted in the sequential bending of coupled planks without scaffolding. Similarly to akin sized bending-active shells (Lienhard et al., 2011), the system was already stable with a few bent and coupled planks. When both layers were placed, discontinuous shear blocks of same thickness were inserted connecting both layers, in addition the splicing joint. The final section consisted in two chords, commonly used in timber gridshells. In this case, bending-active is used in a geometrical approach strictly as a manufacturing affordable technique (Lienhard et al., 2013). Planks are easy to place because of the low torsional stiffness of timber (Naicu et al., 2014) and their deformability around their weak axis although as soon as they get connected, they quickly participate in the global coupling stiffening effect (Lienhard et al., 2011). In fact, the shell initially storing bending stresses will quickly transition from an elastic to a rigid shell, not only by the natural creep process in the timber, but mainly by its drying natural process, which will conform the internal structure of the fibres.

In any case, the lack of specialized manufacturing machines proved to be not a restriction: simple drilling tools and tapes are universal and all the necessary information is concentrated in the hole placement. When properly spliced, relatively short planks, fitting in a van for instance, are not a

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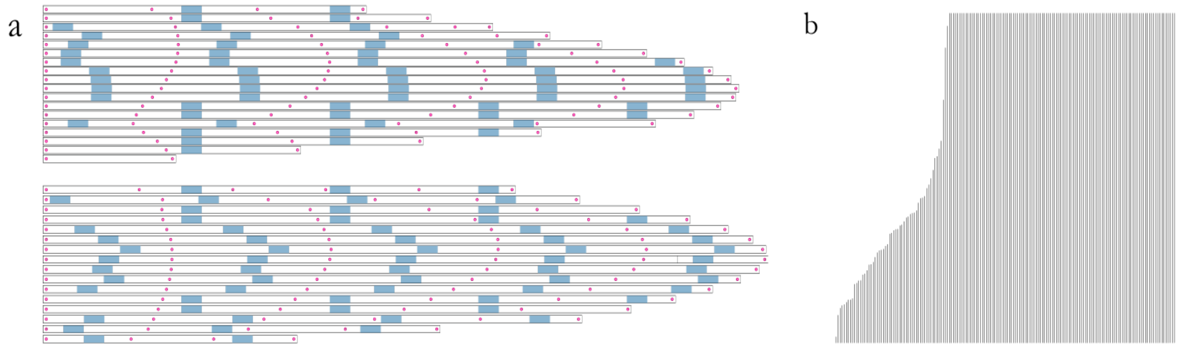

Figure 7.

a. Avoidance of splicing joints and intersection joints b.Scattering of lengths of planks.

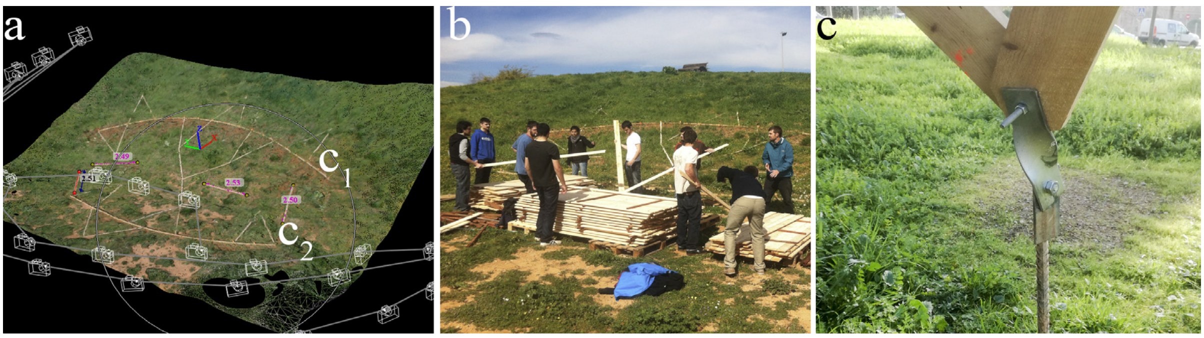

Figure 8.

a. Input curves. b. Sorting of boards. c.Support detail

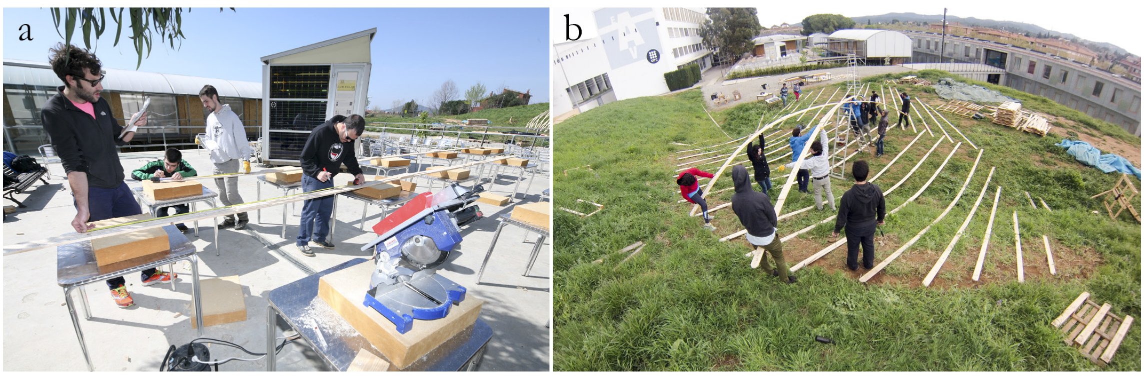

Figure 9.

a.Spliced planks are bored at intersection. b.Erection of coupled planks

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restriction either due to the discontinuous and assembled nature of the final thickened gridshell member. However, the structure stood half a year without any noticeable deformation, but, with the arrival of the rain, the increased weight and moisture, provoked a change of curvature in a relatively flat area. We think the form should have been "weighted" with dynamic relaxation to ensure a more funicular and efficient load flow, or increase the density and number of layers.

Conclusions

-This paper has presented an affordable and low hardware dependent implementation of the geodesic gridshell construction system

-We present a mechanically-free erection method, based in elastically bending by pushing and coupling planks.

-Bending-active structures implemented with green timber can be an affordable strategy to timber doubly curved forming. In this case, slowly carried out by sun drying, transitioning from an elastic bending shell to a rigid compressive shell

-Parametric modelling could embrace the complexity of design restraints in order to provide the best suitable forms according to physical restrictions.

Future research: Investigate the increase of stiffening effect that torsion may provide. More, investigate the control of the grid spacing by controlling evenly spaced geodesics.

Aknowledgements

This research has been supported by a BarcelonaTech FPI-UPC pre-doctoral grant. The work was done under the research framework of CODA with Pep Tornabell, Gerard Bertomeu, Miriam Cabanas, Ramon Sastre and the collaboration of Xavi Santodomingo. Special thanks to our sponsors IncaFust, CeloApolo, and Impresuper. The successful construction of the pavilion would not have been possible without the enthusiastic cooperation of the Ressò team, the ETSAV school and student maker community including Quim Escoda, Omar Avellaneda, Natalia Torres, Laia Gonzalez, Andrea Bernabeu, Oia Pursals, Viacheslav Muraviev, Toni Quirante, Guillem Ramon, Andreu Carpi, Clara Pe, Adil Lazaro, Marti Obiols, Jordi Malet, Gador Luque, Joan Encuentra, Maria Morillo, Jordi Soler, Joan Saborit and of course our official photographer Andres Flajszer.

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Figure 10.
Long planks are conveniently deformable until they get bent and coupled.

Figure 11.
Bottom layers. Bolts are pointing the normal vectors, and waiting for the upper chords.

Figure 12.
a.Sometimes many hands are needed to give the needed twist to a board.
b.breakages due to grain can be repaired on the fly, with more more shear blocks. c.detail of two beams arriving to a support.

Figure 13.
Final rigid shell after summer.

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Deployable Structures System, Hexagonal X-frame. Three Case Studies

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Abstract

This article is part of a research that seeks methods to control movement of the deployable structures with textile membranes. The maximum strength of the textile will be used to stabilize and control the movement of the deployable structures. This research proposes 3 cases of study, starting with its geometric design and finishing with the end result of a low cost prototype to scale. The idea is to analyze and study the morphology of the hexagonal module with straight bars. With support of algorithmic design and physical models, make the verifications of movement and geometry. It aims to design 3 different geometric configurations, starting from the hexagonal module. It also seeks to analyze the mechanical behavior of its joints and check their deformation with the construction of intermediate-scale prototypes. Finally, it is expected that tools of support will be used for the design of x-frame deployable structures with hexagonal modules. The construction of the prototypes was done with the help of the students of the Valles School of architecture. ETSAV.

Keywords

Deployable, X-Frame, *prototypes, structure, pavilion,*

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Introduction

Nowadays deployable and transforming structures are more common in architecture. The quick assembly, flexibility, the lightweight materials, and the easy transportability are the most important features of these systems. The deployable structures with straight bars enhance these features, occupying little space when the structure is closed.
This research seeks different morphological possibilities of deployable structures with straight bars, with approximations of habitability, either as an independent module that allows repetition to form a habitable whole, or as independent elements, which will help to build systems of habitability, whether being with roof elements, facade or walls of the interior of habitable systems.
The morphology of deployable structures is related to the concepts of solid geometry, and this is the starting point of this research. Other essential points are the examination of the transformation and the search for appropriate geometries for a system of habitability. The exploration of form is also very important in this research since it seeks to surfaces of double curvature, synclastic surfaces or anticlastic surfaces with systems of straight bars as a solution of a container element. As shown in figure 1.

Deployable structures systems articulated with straight bars have two possibilities grouping surfaces, square and triangular module or hexagonal module in their transformation. The groupings in both cases make it possible to solve double curvature surfaces; therefore the examinations made in this research blend both groups and explore new possibilities of more complex geometric configurations, not only at surface but also with spatial configurations of the object to make a self-supporting structure, which is habitable.
The recommended solutions for the joints of the deployable structures are designed according to the number of bars that reach each node and the structure of the proposed material. The idea is that they are easily manufactured and support the process of folding and unfolding required for the proper functioning of the system. Additionally they should serve as anchor points or support of the membrane or fabric.
The methodology is experimental, with the development of physical and digital models, and it supports parametric design tools. In the first phase it is the search form and the digital checking of the geometry and movement of the structure in its fold and unfold. Secondly, developing the scale prototypes, and exploring the construction details, fabric membrane pattern and the tension movement of the structure. Figure 2.

The starting point is the theoretical basis of the deployable structures. This has been submitted since the 60's Buckminster Fuller is a source of extensive information of geometric studies. He designed innovative structural systems such as tensegrity and geodesic. Therefore this background information is part of this research study. Similarly, another important character was Emilio Perez Piñero, a pioneer in designing deployable structures. His designs have all been recommended and investigated in the transformable architecture.
Nowadays, there are research groups, developing new proposals of deployable structures with straight bars, to such an extent that there are specific conferences for this type of architecture. In September 2013 the first International Congress of transformable architecture was celebrated in Seville, Spain. Figure 3. This was in order to connect the sources of research in these structures and to share information. In general there are two very clear lines of research. The first is focused on parametric design and theoretical analysis of deployable structures. The second is the problem of the joins in the development of full-scale prototypes.

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Figure 1.
Deployable Structures System, Hexagonal X-frame - typologies.

Figure 2.
Proposal microarchitecture with Hexagonal X-frame

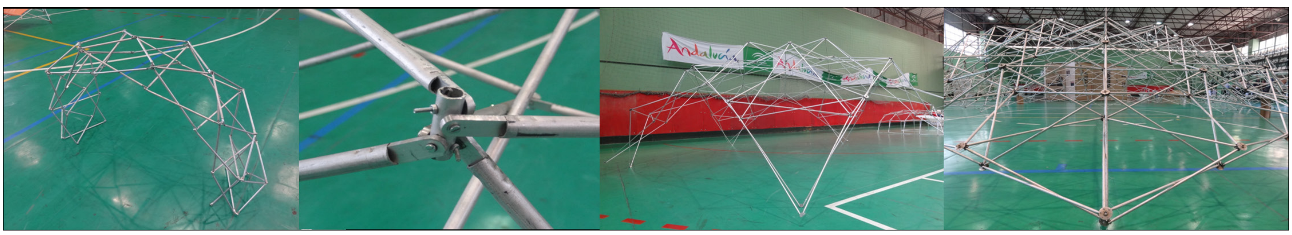

Figure 3.
Prototypes, Felix Escrig. Conference Transformables 2013. Sevilla, Spain.

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This research aims to approach these two problems and suggest a methodology using 3 case studies. The final phase, is the selection of a prototype. Its construction on real scale will lead us to solve in an integral way the entire system, and will enable us to check each one of the solutions through software and digital design which are seen to be an approximation of reality.

Geometry and parametric design

The design process and geometric exploration of the hexagonal X-frame, begins with the analysis and study of the theory of solids. Understanding the concepts of transformation, duality, tessellations, non-continuous groupings and more games solid geometric, is the basis of this initial study. The theory of solids, is directly related to the final configuration of the Hexagonal X-frame module, as well as the possibilities of groupings, checking of movement and control, the final stability and its relationship with the textile membrane or skin. Therefore the beginning of this research consists of the geometric understanding of the Platonic solids and archimedean. Regular and non-regular. As shown in Figure 4. The deployable system structures of straight bars have two possibilities of grouping in surfaces: square and triangular modules or hexagonal modules in the transformation. The groupings in both cases can be solved through double-curved surfaces. The investigations made for this research, mix both groups and explore new possibilities of more complex geometric configurations, not only superficially but also with spatial configurations that make the object a self-supporting structure and also a habitable one. Finally for the case studies, the hexagonal X-frame model was selected.

Geometrical exploration has two phases. The first one is a practical, which consists of tests using small models. These are made with sticks and flexible plastic pipes. The joints are made with elastic bands as in Figure 5. This first approach serves to check the movement and aids understanding of space. Deployable solids, flat mesh, and sinclásticas were designed, as well as modular configurations and spatial groupings.
The second phase is aimed at the parametric design. At this point the objective was to design basic modules. Several alternatives were designed in order to obtain a variety of modules, which eventually led to groupings. The geometry for the design of the modules consists of circles. X-frame bars and their movement are always registered in a circle. The parametric design was made with Grasshopper, under the platform of rhinoceros. Figure 6.
The units of hex module X-frame proved to be the most stable showing motion and tension. They also proved to be the best option of horizontal, vertical and spatial groupings. In the process of design and exploration of the hexagonal module, two groups were found: the first being the continuous spatial groupings (that is, filling the space completely) and the second one being non-continuous spatial groupings (allowing empty spaces in space or on the surface).

This part of the research allowed further exploration of the X-frame deployable structures and also provided alternative morphologies without a specific use (important in detecting potential groups in the hexagonal modules X-frame).

Physical Models and Digital Models

Following on from the geometry exploration process, the hexagonal module was chosen for prototype designing. The hexagonal module can be of three types.

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Figure 4.
Deployable Structures System, Hexagonal X-frame - Exploration.

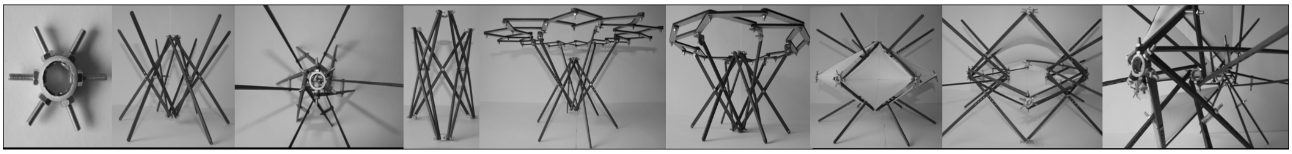

Figure 5.
Development of scale models - Hexagonal X-frame.

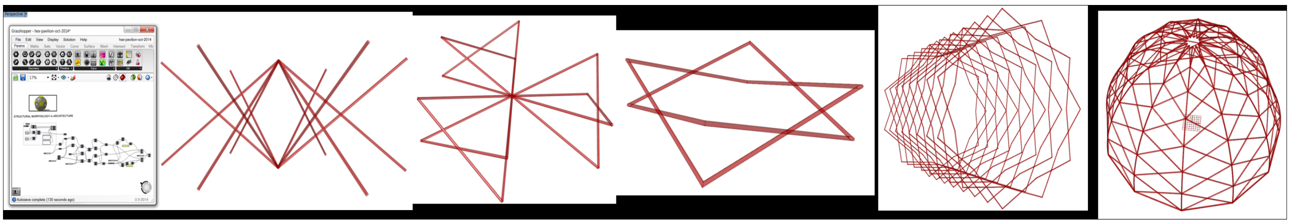

Figure 6.
Parametric Definitions whit Grasshopper software. Exploration.

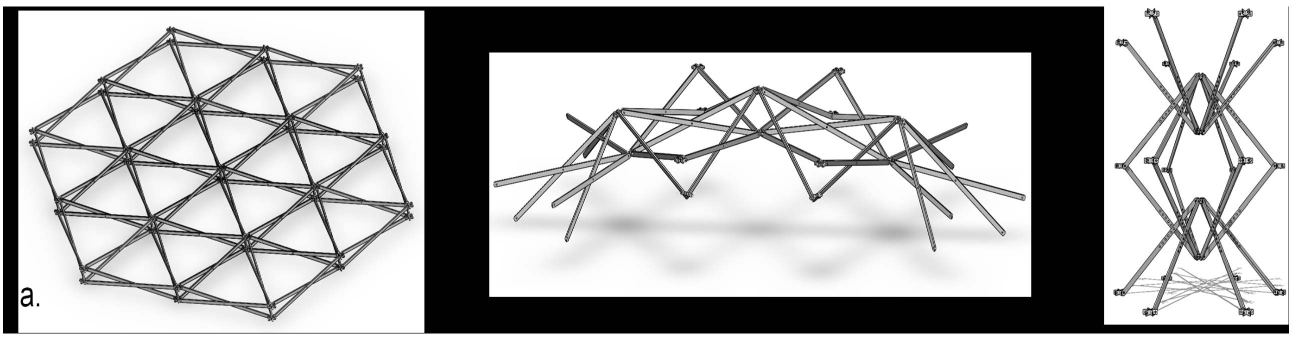

Figure 7.
a. Symmetrical hexagonal module. b. External eccentric hexagonal module. c. Internal eccentric hexagonal module

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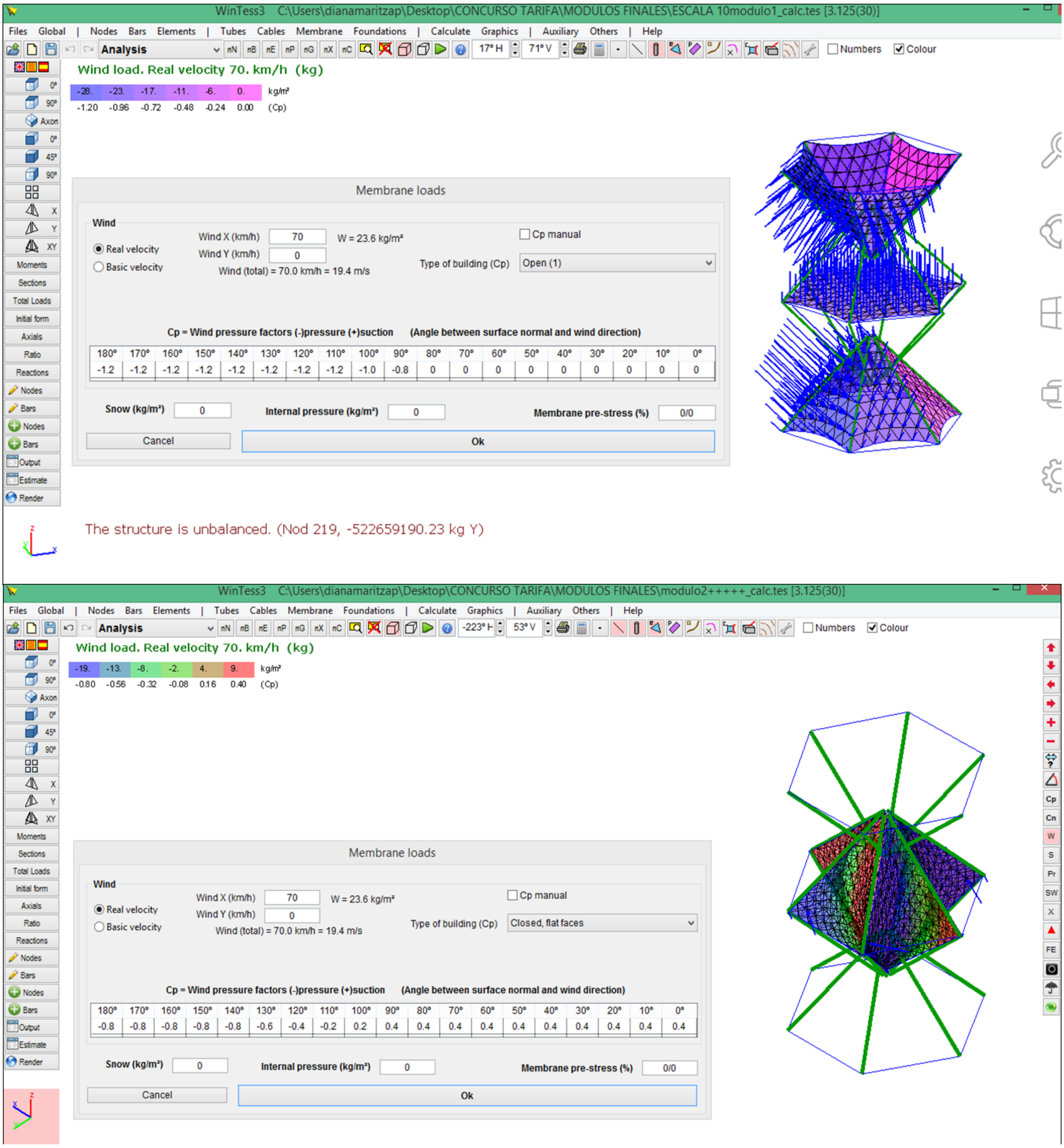

Figure 8.
Theoretical analysis of the hexagonal module x-frame in Wintess, software by Ramon Sastre Sastre.

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a. Symmetrical hexagonal module. This is formed by six pairs of straight bars jointed at the center of the distance of each bar. This configuration allows for flat meshes, linear and spatial groupings with orthogonal displacement.
b. External eccentric hexagonal module. This is formed by six pairs of straight bars jointed and oriented toward the lower or upper face of the module. This is to say short bars are opening or closing, up or down the module. This configuration allows for groupings according to curving eccentricity. Therefore, the greater the eccentricity, the bigger is the curvature. It also allows for sinclásticas and anticlastic surfaces to be made.
c. Internal eccentric hexagonal module. This is formed by six pairs of straight bars jointed with eccentricity at the center module. That is to say that the central diamond is smaller. This configuration allows flat mesh, linear and spatial groupings to be made with orthogonal displacement. The difference between the first options and this one is that "c" allows you to adjust the diamond to a smaller or larger size, as required by the diamond inside the hexagonal module. This type of module is useful for non-continuous spatial groupings.

The development of physical models, helps to understand the path of a module when it is grouped. It also allowed for a low-cost design of a piece of hexagonal union, for the production of the models. The joint is made of pcv cut rings with 3/4 inch diameter, with manual drilling with angles of 60 °. This piece allowed models to be further developed and made with more rigid materials, and also enabled us to see the deformations of the bars according to their groupings.
Digital models were also created to support the theoretical analysis module. Stresses, displacements and deformations of the module. This stage follows on as a development of this investigation, providing us with information of how the module would behave in reality. On the one hand, we have the mechanical behavior of the bars, made in SolidWorks Simulations. Finite Element Analysis (FEA). As shown in Fig. 8. On the other hand, a study of wind loads and a proposal covering the membrane module. This analysis is made with the WINTESS3 software designed by professor Ramon Sastre Sastre.
This item is part of future research, which is expected to have a theoretical analysis of the x-frame hexagonal module and also of its mechanical behavior in continuous and non-continuous groupings. For the current stage of the study, these results served as reference for the development of scale prototypes.
In the FEA of the x-frame hexagonal module, as can be seen in Fig.ure 9, the lateral displacement and torsion bars are subjected to a point load in the center of the joint. The maximum stresses at the ends of the bars can also be seen. With this analysis, it can be concluded that the design of a connecting piece to prevent displacement of the bars and to prevent it from collapsing is subjected to the twisting of each mule.

Case study 1 - Domo Erizo

Sinclástic design surfaces from a system formed of straight jointed bars. It is formed by external eccentric hexagonal modules. The work was completed in collaboration with students from PEI Javeriana University of Colombia in the summer of 2015, Barcelona.
The definition of the geometry of the Pavilion Erizo is given by a hexagonal base module. The module consists of six eccentric scissors node attached to circulate tangentially as shown in Fig.ure 10. This basic unit is repeated six times to form first a first hexagon, which is repeated ten times forming a triangle in plan and at the end of this geometry, to each of its ends, two more units are added. As can be seen in the diagram, it generates a

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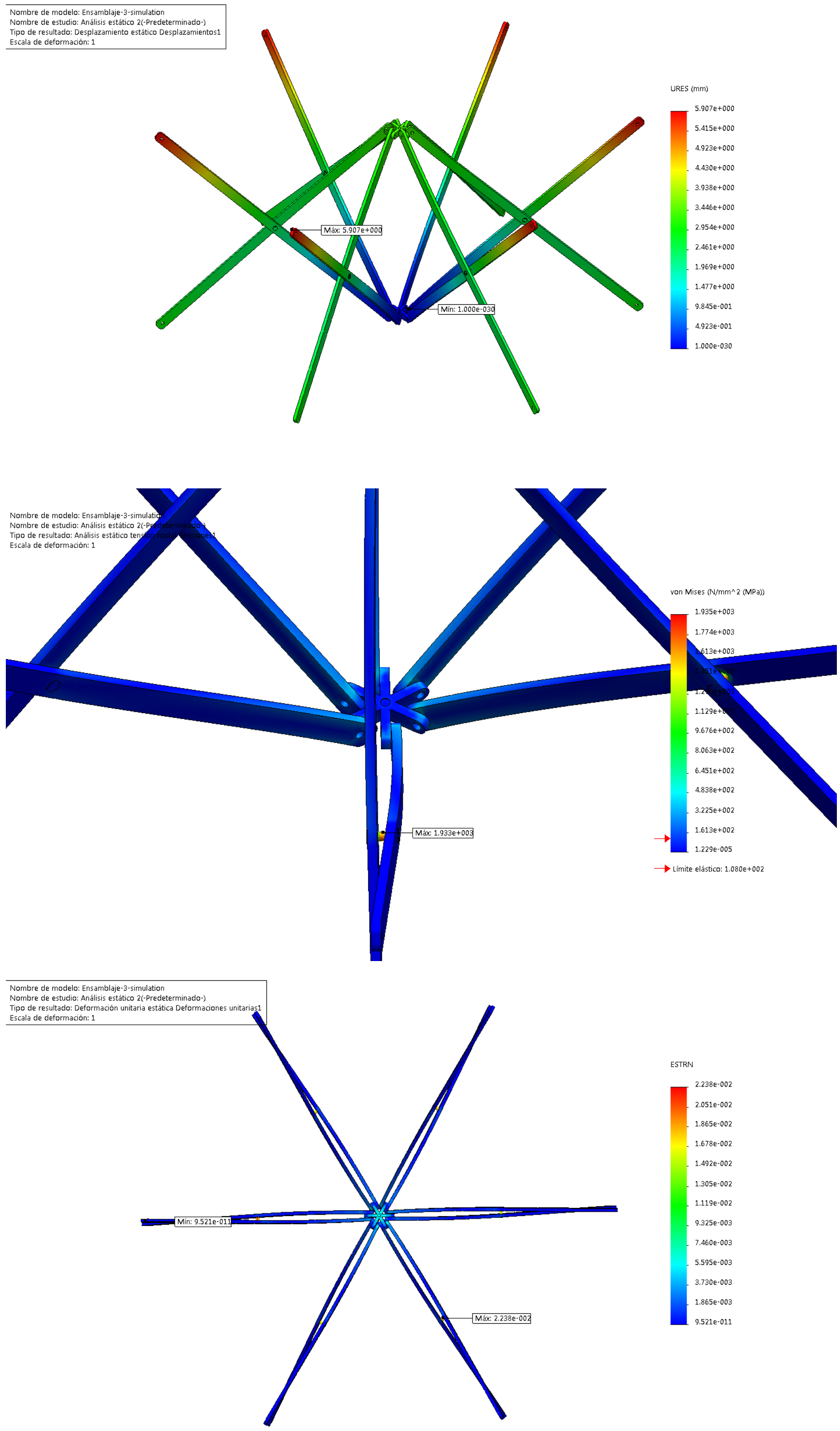

Figure 9.
Finite Element Analysis (FEA). a. Tensions. b. Deformations. c. Displacements

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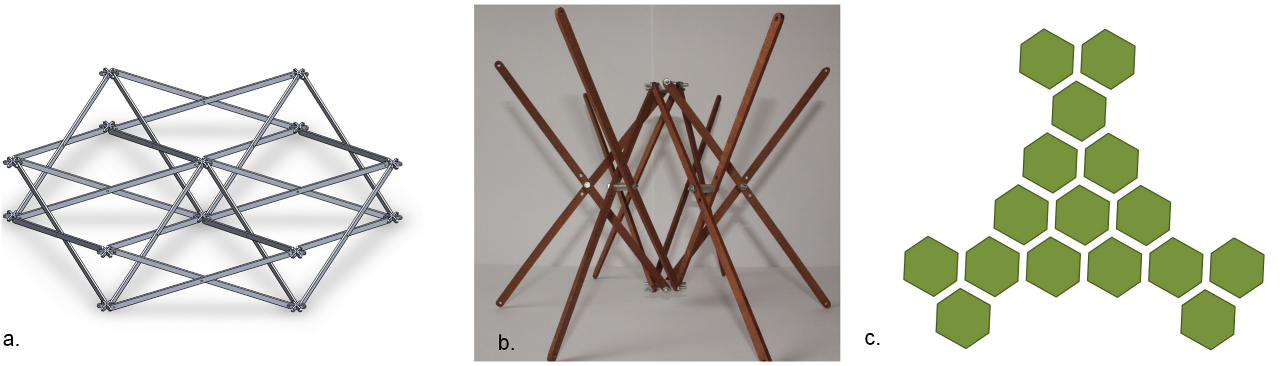

Figure 10.
Geometry Dome Erizo.

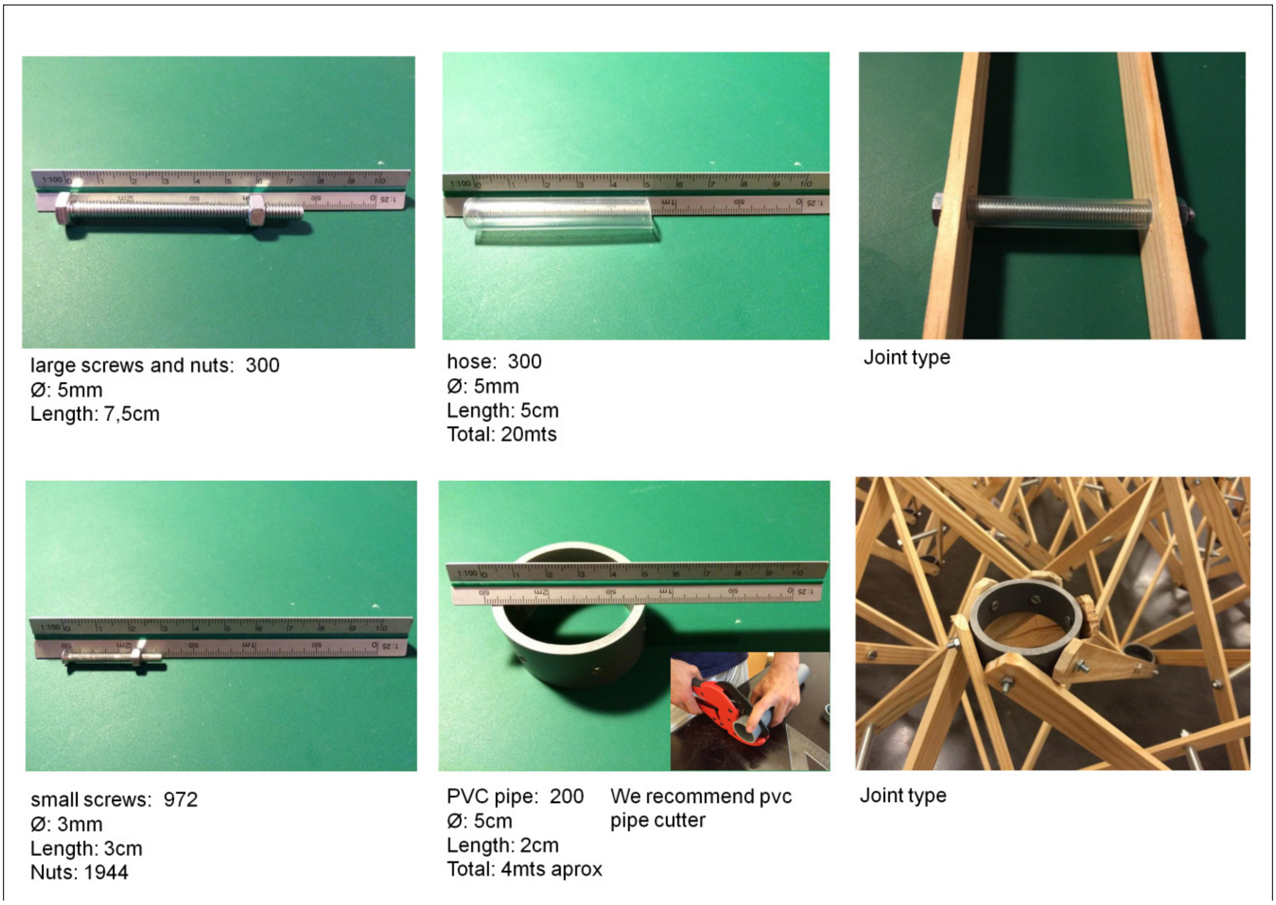

Figure 11.
Materials

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final structure consisting of sixteen basic modules.

The Erizo Pavilion develops through all joints and bars of the same characteristic, whereby the assembly and disassembly is fast and versatile. The specific characteristics of the system used in this structure corresponds to straight eccentric hinged together scissors system generates such curves depending on the eccentricity of the articulation between each bar composing the scissors. El module is formed by six pairs of scissors in wood that are joined at their ends to the knot of PVC plastic tangentially, as we can see in the scheme.

The materials used to build the scissors were: pine wood, nuts, bolts, plastic hoses, PVC pipes, plastic caps and angels. As for the tools, they were sent to cut the wood for better timing. Then the students were ordered to cut PVC pipe to generate knots. As shown in Figure. 11. Also with the defined measures they cut the plastic hose, which along with long screws serves as a separator between the wood elements of the scissors. For the preparation of the material, it had to be measured and sent to cut the wood, then labeled and made the holes of the scissors.

Pieces of wood were joined by long screws which were separated by the plastic hose. Short screws were used to attach the timber to the knot of PVC. The module was formed by six pairs of straight scissors, which were joined together tangentially to a circular PVC knot. After having the six basic modules forming the first hexagonal unit, this process is repeated until the final sixteen modules, which will join concentrically, as shown in the photos. To assemble the deployable structure, plastic angel caps were used to fix end result of sinclásticas geometry. Figure 12.

For the manufacture and assembly of equipment Erizo Pavilion, the team was divided into six groups, each of them responsible for the first six modules, which would later on unite to form a common ground of sinclásticas and eccentric straight scissors. The preparation of the material took two days and the assembly was done in one day. All work was conducted by a team of nearly 60 students. Figure 13.

The structure had several problems. The most obvious was his geometry. The geometry did not complete a circuit or circle. Therefore it was unstable due to its weight. This was solved by using a lock on certain benchmarks of geometry. It was clear that the pop-dome system needed an additional structure to control for when the structure element closes or expands. A system of motion control is needed. The proposal of mechanical locking is able to stabilize the geometry and the natural shape of the dome.

Case study 2 - Tower Hive

Tower Hive, is a proposal that was presented to the IFAC (International Art Festival and construction). www.ifac.me - The tower project was to design a visual point of reference for an ecological village in Bergen, Netherlands. The proposal is designed using internal eccentric hexagonal modules. That is to say that it allows for orthogonal configurations with eccentric bars. This module was ideal for making a vertical linear configuration and for giving the impression of floating modules, as shown in Figure 14.

The Hive Tower can be used for public lighting, a garden element, or a city landmark (outdoor public space). In all the cases will be a "hito" or reference or meeting point in the city.

The landmarks within the urban space are pieces of unique architecture designed so that their height stands out from the other buildings around. The function of these benchmarks is to serve as guideposts in the urban space. The ordinary citizen may be found within the city oriented through urban elements.

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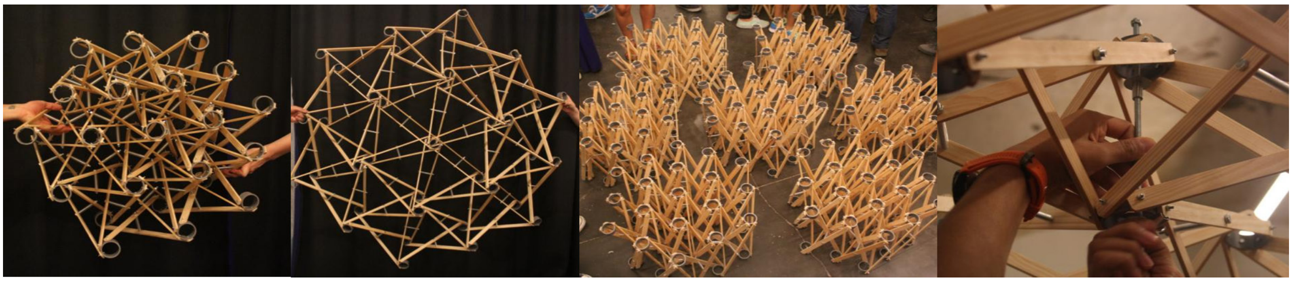

Figure 12.
Dome Erizo. Construction process.

Figure 13.
Dome Erizo. Views.

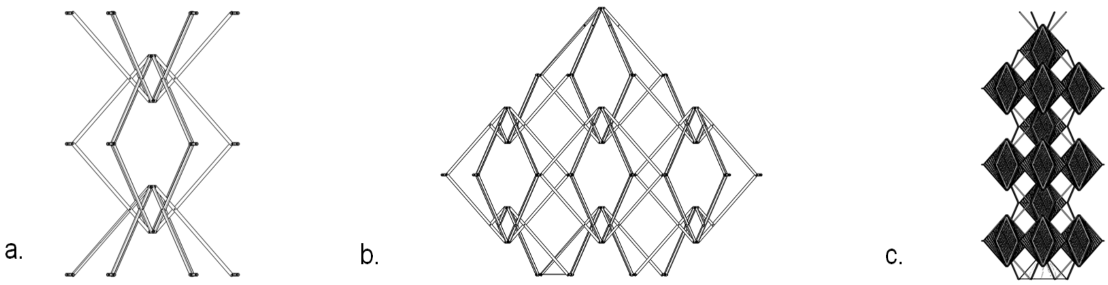

Figure 14.
Fig. 14- Geometry whit Internal eccentric hexagonal module.

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Figure 15.
Tower Hive - Construction process.

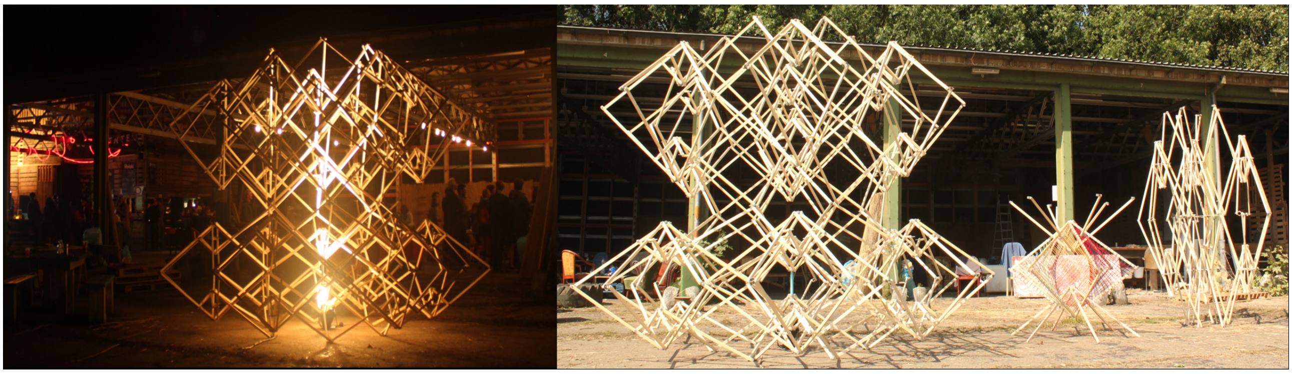

Figure 16.
Tower Hive - Viewe.

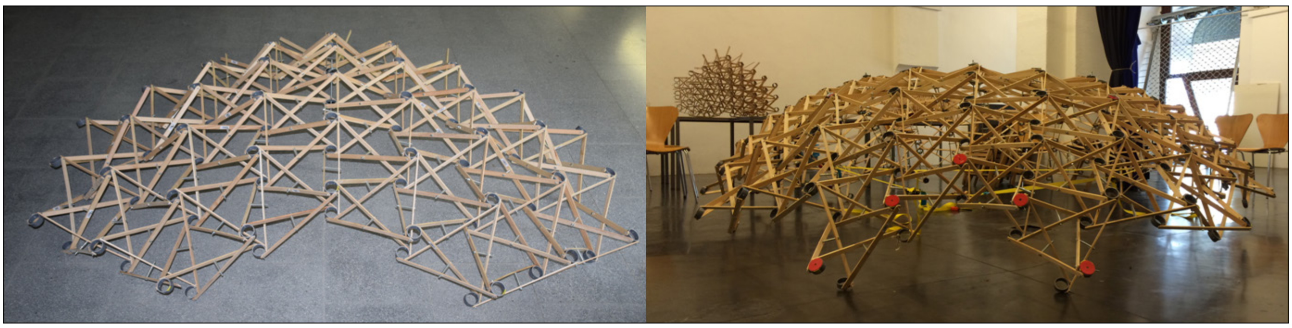

Figure 17.
Shells triangular base and a hexagonal base.

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The Hive Tower could be a good example of a landmark or public lighting as it has two very important characteristics: height and light. Both characteristics help to guide people through the city.
The main idea is to build a tower with deployable system scissors, understanding the concepts of the practical part: the fold-ability and retention, the morphology of the deployable structures and the geometry. All done with the help of the software used for parametric design and physical scale models.
Hive Tower is an rising deployable structure, consisting of a system of articulated symmetric bars grouped in a hexagonal base. The bars are 1 meter long and a 40mm x 15mm section. The articulated rod system allows the structure to fold and unfold quickly with the use of human force. Accessories for bars joints are designed in aluminum or recycled materials such as pvc. Hexagonal unions, receive 6 pairs of jointed rods to setup the whole system. The same connections are used as joints at the ends of each bar system. The bars joined at the center of the tower, form a structure, which serves reciprocal movement limit of the system.
The construction of the tower was made with the participation of fifteen students from different countries who participated in the festival. The proposed methodology was to make a production line for enlistment of material. The wood used was plywood. Pvc rings. And the union fittings in galvanized steel. Figure 15
The assembly of the structure is made by composite modules. The tower is divided into three parts for better handling. Each compound module was made up of 16 x-frame hexagonal modules. Each module individually could be folded and unfolded easily. When modules were fixed on top of each other, problems presented themselves. The pin structure was affecting the bearing capacity of the bars. Buckling was seen at the bottom, in the lower load bar because of overload, and there was also torsion in the bars in the nearest parts PVC rings.
The problem of overload on the structure was solved with a locking system, since the weight of the structure was forcing the folding system. This prototype was the need for a motion control system. With an additional element to the frame the loading of the structure is stopped by its own weight. The experiment was done with a small module using a mesh as a future cover for the community of the town. This exercise was surprising since it managed to achieve the load control of the of the module by its own weight (as shown in Figure16).
At this point of exploration with real prototypes, we considered the need for a motion control system for deployable structures. At the moment they are focused in situ, temporary mechanical solutions. The tower mount was put together using only two out of the three modules. The third module was used to show the movement of the structure. A height of approximately seven meters was achieved when it was unfolded, and about 4 meters when folded. As an exercise of morphology and constructive solutions this step was very gratifying and very helpful to learn the real physical behavior of a deployable structure to intermediate scale.

Case Study 3 - Mobile Hanging SMiA

Mobile hanging was an exercise in recycling and reuse of the dome. Normally the construction of these pavilions or approximation exercises, have a short life cycle. The Erizo dome was an example of this reality. This research and the research group SMiA (Structural Morphology in Architecture) wanted to give a new use to the structure and turn it into a temporary exhibition in the main hall of the ETSAV. The idea was to cover double

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broker height ETSAV. For this, four sinclásticas shells were designed: three shells of a triangular base and one of a hexagonal base. The idea was to form an undulating anticlastic surface using the four shells. Figure 17.
In this prototype we were looking to check the behavior of the structure and the wall units from a single point. The assembly process was relatively quick as in three hours it was finalized. Each of the shells, began to shape in their own particular way due to gravity. The shells achieved their maximum opening point, making it easy to deploy. The structure showed no major deformations due to own weight as seen in the previous two proposals. Similarly, locking elements were considered to prevent movement. This ensured greater stability of the mobile. Currently the structure is exposed for a period of 5-6 months. As shown in Figure18.
The proposition serves as an exercise to explore the possibility of making and designing a system of deployable hexagonal modules structured with x-frame, which can be assembled and disassembled quickly with the same elements but different configurations. The idea is to use equal linear elements (bars) and one standard binding system, different types of habitats or constructed spaces in order to give the structure durability and reusing of this.

Conclusions and future research

The experience of building prototypes to a medium scale of deployable structures is very positive. Scaling, the design of the joints, the mechanical behavior of the prototype, its weight, the transition from the digital to the prototype, and deformations, are some of the things, which can be seen in this practical. While the propositions were raised as inexpensive prototypes, they were considered the best materials and therefore its investment was something to consider. This processing was possible, thanks to collective resources.
The change of scale. This is one of the most valuable conclusions. Physically verifying the results of the theoretical analysis FEA (Finite Element Analysis) which with the development of a small-scale model, are imperceptible deformations or displacements. Also, having control of the actual or approximate weight of the structure, the joints, and accessories. However, when changing the scale it is more difficult to control the movement of the structure, so it is necessary to consider motion control systems.
Motion control systems. The hexagonal system x-frame deployable structures, require additional elements to the structure to control its maximum open point or minimum point of closure. The hypothesis is to integrate the mechanical characteristics of the membranes and resistance to the maximum stresses, so that these serve as a maximum aperture control system. The three case studies presented stability and movement control problems. In all three cases the use of additional elements was necessary to block the movement and stabilize its shape.
Deformation and torsion bars. The changing step from working with models to working with a prototype of intermediate scale, requires checking the dimensions of the elements, materials and designs of joints. The drop-down structure system requires designing of its unions. With designs made to prevent displacement of the bars and reduce deformations.
Finally, as further research, we want to complete the theoretical analysis of the hexagonal module, and if possible physical analysis of a laboratory scale module. The aim is to include in these analyzes the behavior of the module integrated in the membrane textil as a proposition of a roof.
The idea to design a deployable structures system hexagonal x-frame like a construction system and propose mechanisms for motion control, integrated membrane systems and developing clusters as approximations of habitability are the future of this research. This is the idea of a modular, compact and lightweight construction system. Fig.ure 19.

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Figure 18.
Mobile Hanging SMiA. Views.

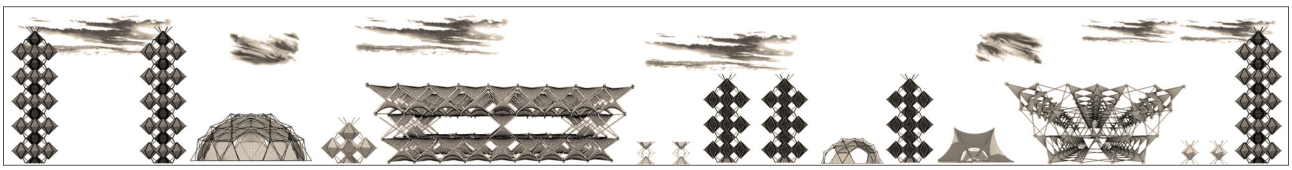

Figure 19.
Future hits - Portable and deployable cities - Microarchitecture.

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Post-industrial robotics: the new tendency of digital fabrication for exploring responsive forms and materials through performance

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Abstract

The contribution proposes the experimental results of research on robotics manufacturing issues for the realization of informed architectural organisms on a 1:1 scale. The pavilions Fusta Robotics and Digital Urban Orchard and the technological system In.Flux represent the results of tests in which material, environmental and structural performance inform the computational process and the consequent materialization. The two pavilions, both wooden, constitute the physical implementation of different functional programs realised through a collaboration with industrial partners. Fusta Robotics is the result of a collaboration between industry and universities for the tectonic experimentation derived from the use of local non-engineered material. Digital Urban Orchard is the formal expression of a complex functional program arising from the relationship amongst form (shape), function and context for a new concept of socialization space and food production within the agenda at the self-sufficiency in Barcelona. Finally, through the In.Flux prototype, we investigated the relationship among formal generation, structural analysis and robotic manufacturing for the realization of concrete free-form structures. The analysis of the prototypes opens the debate on the role of IT in the post-digital era when the design process manifest through the control and management of the flow of information affecting the digital computation and fabrication and the material behaviour. The resulting theoretical assumption considers the architectural form as the result of a diagram of forces where the achievement of the performance is the driving parameter for the formal geometric exploration. The continuous variation resulting therefrom is informed by performance parameters that define a new aesthetic which represents together the manifestation of objectively measurable performance parameters and the power of the tool through which the form is generated.

Keywords

Performance-based architecture; flexible models; optimization; data-driven strategies; robotic fabrication.

Note

The paper is a critical synthesis of parts previously published at conferences and seminars. The project Fusta Robòtica was presented to the International Conference REDS 2 ALPS as paper and poster while the project Digital Urban Orchard was presented as poster to AAG Conference at ETH in Zurich. Both projects have been subject of study in further paper to the conference Colloquiate 2016 in Matera, Italy.

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New paradigms for responsive architectures between computation and digital fabrication

The proposed contribution investigates the sector of product and process innovation which ranks as a priority to identify and define an applied methodology that combines digital computing, optimization and innovative production methods in order to determine the potential and critical issues related to a possible introduction of such strategy in the construction process or for what concerns the definition of a new concept of responsiveness. The recent publication "Parametricism 2.0" (Schumacher, 2016) has highlighted the beginning of a new testing phase that targets the use of computational-algorithmic tools, in their theoretical and practical aspects, for the resolution of specific environmental and social issues returning to deal with issues which warranted the birth of digital computing itself in the 70's (Frazer, 2016).

The ability to process information and then to use the data as guiding elements of the design process and not as add-on to use later on (Deutsch 2016) opens many, and largely unexplored, possibilities for environmental and technological design in all project scales. The theoretical assumption defines the architectural shape as a result of a diagram of forces (Thompson, 1992) and opens new investigation fields in relation to the possibility of creating and implement performative architectures, performance - based (Hensel, 2010). Hence, the geometrical and formal generation and exploration has the achievement of tectonic, structural, material and environmental performance as a driving parameter. It can be optimized in relation to a "space of possibilities" (De Landa, 2011) defined by the designer himself through a project goal (Kolarevic, 2016). The generative process offers the opportunity to explore complex and informed geometries in a flexible and fast way, to investigate natural phenomena, transforming the material from a passive recipient of shape to a design agent, such as driving element of the creative process, through the exploration of its mechanical, structural and behavioural features (Menges, 2012).

Based on this new paradigm the term performance takes on a new meaning. Talking about performance means to relate various aspects affecting the project by watching and learning from the natural and biological world: starting from the material, structural and spatial organization up to the environment and energy, the performance can inform the architecture and make it similar to a biological organism (Hensel, Menges & Weinstock, 2010). To transfer a performance - oriented architecture from the digital to the physical world, we must establish a new relationship between architecture and manufacturing among modern era paradigms. This need arises from the impossibility to use mass produced identical building elements as a solution to be applied in any context, even though it is subjected to input and dynamic variables of various kind. Through this methodological approach, we may have complex and

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responsive geometries in relation to external variable inputs, a digital customized process able to convert these morphologies in simple geometric elements and a highly performing and competitive manufacturing process (Gramazio, Kohler, 2014). This way the manufacture process will be informed by the performance defining a new concept of responsive architecture where the focus is placed on the generative and computational process, based on data rather than electronic and kinetic devices to be applied later on. To transfer a responsive Architecture from the digital to the physical world, we have to interconnect various skills and transfer to the field of architecture technologies used in other areas.

The architects go back to deal with problems related to the construction process, "the design of the process", and not only with the creative and compositional stage bringing back the division between mental and manual labour that has existed since the Renaissance with the models proposed by Leon Battista Alberti and Brunelleschi. The Dome of "Santa Maria del Fiore" in Florence made by Filippo Brunelleschi in 1436 is an example of a process-oriented design in which the architect has been involved in the whole process. From the concept and creative stage to the design of technological details of a custom machine realized in order to be able to materialize an architecture that responds to spatial and structural performances, not possible with standard procedures and technologies.
Learning from the Brunelleschi's dome, the fabrication process becomes a design input that informs the design process defining a new concept of responsive architecture that exceeds the logic of the assembly to achieve certain performances that may not be the same for each project and each application context. If the production processes derived from the industrial revolution are performative about costs and times of production, at the same time they are not suitable to manage the customisation and complexity of the components. Hence, the necessity to investigate and experiment manufacturing and design innovative processes able to subvert the concept of mass production of industrial origin. By doing so, it is possible to expand the range of materials used and discover new applications for traditional materials in order to give life to informed and sustainable processes. That enable a shift from serial mass produced components to a design that can take into account the performance of the materials, the application context and the characteristics of variables that inform the design process for which it is not possible to resort to standard prefabrication (Gramazio, Kohler, 2014).

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Figure 1.
Robotic fabrication process: pick, cut and place. b. Final prototype. Source: Andrea Quartaraa.

Figure 2.
a. Robotic fabrication process. b. Wood structure assembled on IaaC rooftop Source: Andrea Quartara

Figure 3.
a. Robotic Milling process b. Final prototype at AA Hooke Park Campus. Source : Elif Erdine

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Digital manufacturing, now a well-known process in the architecture and industrial design sector, allows achieving a high degree of variation and complexity through the direct connection between geometry, virtual model and physical reality. The evolution of 3D Printing, from printing small items to printing architecture prototypes in 1-to-1 scale and the additive and subtractive techniques that characterize the world of digital fabrication (Naboni, Paoletti, 2015), are the demonstration of this theory. The connection between the generative process and the manufacturing process does not follow a formal evolution without logic and compositional relationships but rather uses the machine as a medium that allows producing complex geometries informed by optimization processes. One of the latest experiments in the digital manufacturing field linked to the world of construction is the introduction of industrial-robots. In 2015, the research conducted on these issues by Professors Fabio Gramazio and Mathias Kholer at the ETH Zurich has reached its 10th anniversary and has achieved such a high testing level to induce the Swiss government to invest huge resources in the NCCR project, 2015-2018, that will have the full-scale application of digital manufacturing robotics as output. The industrial machines, anthropomorphic robots, used in the automotive field since the 80's (Gramazio, Kohler, 2014) to perform specific tasks are reprogrammed and used to transfer digital models in the real world through this direct link.
Thanks to the abilities of the machines, it is possible to build and materialize complex and informed geometries.

Responsive architecture: methodology applied for the realization of experimental structures

The proposed methodology was tested by carrying out a series of experimental architecture at 1: 1 scale through which it was possible to define the potential and critical issues coming from the application of the theoretical assumptions. The construction of the prototypes, Fusta Robotica (Figure1), Digital Urban Orchard (Figure 2) and In.Flux (Figure 3) represents the practice of a new design paradigm based on the information of the process that sees environmental, structural, tectonic and space performances as a factor driving the entire design process. The performance criteria derived from the material, the structural and environmental behaviour have informed the computational process, subsequently materialized using a generic machine, anthropomorphic robot, able to transpose responsive digital models with different functional programs in reality, through a non-industrial setting and using simple, irregular and low-engineered elements. The prototypes built as explication of the theoretical assumptions are the result of an

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informed process among performance yardsticks and a new digital production method able to guarantee quality, flexibility and efficiency (Scheurer, Schindler & Braach 2005).

Fusta Robòtica: material - informed design through design information and robotic fabrication

The Fusta Robòtica[1] prototype is the first wooden structure built using robotic manufacturing in Spain. It was born from a collaboration between the IaaC, Institute of Advanced Architecture of Catalunya, and an industry of the sector as a material and tectonic testing to be exposed at the Setmana de la fusta 2015, with the intent to show the potential derived from the application of robotics manufacturing in the construction of wooden structures.

Objectives of the research were represented by the promotion and enhancement of the Catalan wood, sustainable and of high quality, by the exchange of knowledge between industries and research centres for the innovation in the production and distribution of the model in order to test new formal codes using local material. The material used to experience a new tectonic expression, consisted of simple wooden rods, irregular and low-engineered by the size of 38 mm x 38 mm x 2000 mm. The pavilion, formed by about 1000 wooden rods of variable length, is the result of the elaboration of a complex geometry, hyperboloid, in which the rotation of geometric continuous elements has allowed to obtain a dynamic spatial configuration. The entire design process was informed by characteristics and properties extracted from the material through a series of experiments, analogical and digital, aimed at the understanding of the behaviour of the material and the structural system. The use of this sustainable material, non-engineered for the use in the construction industry, has allowed us to analyse the potential and critical issues coming from the application in Architecture as well as to inform the design process.

Through the experiments conducted on the material in accordance with the manufacturing method and the available tools within a non-industrial setting, in the specific case wood provider, circular saw and drill, it was possible to define some critical issues.

For example, the variation of the curvature following the drying process of the wooden rods and the need to maximize the resistant section of the components to increase the structural rigidity and the load carrying capacity due to the scarce structural quality of the material. In relation to this, the design process has been informed using a redundant, hyper static structure composed by a multitude of small elements in

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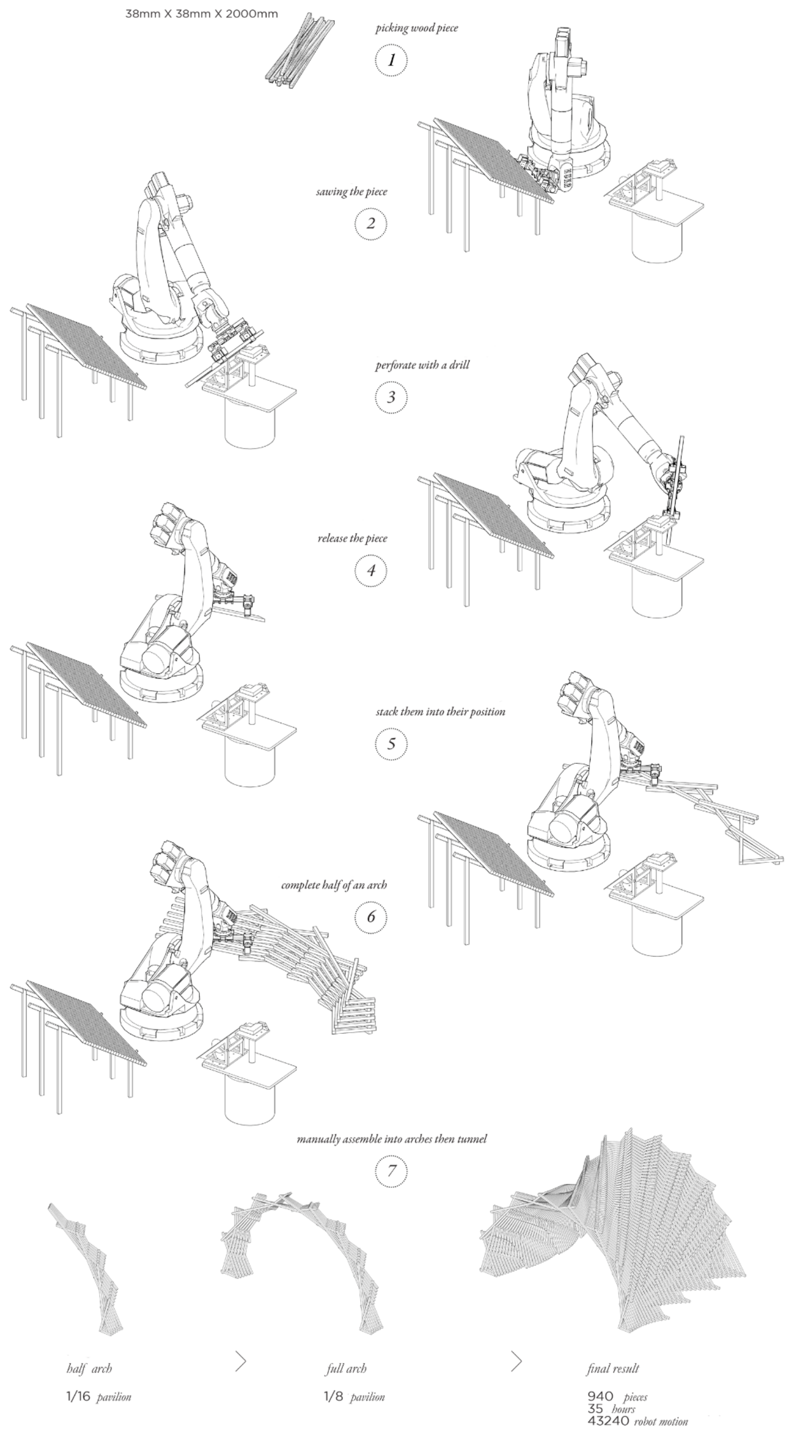

Figure 4.
Fabrication loop process. Stick picking, 2-side cut, drilling and stick placing.

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order to avoid structural problems due to excessive bending of the wooden profiles. To maximize the resistant section of the components in correspondence of the structural nodes we used nailed joints while the discretization of the shape in eight sections with a constant thickness has allowed optimizing the working space of the robot room avoiding collision problems. The design is informed and optimized within the characteristics of the production method used, the available tools, the working area, the characteristics of the material used and the structural behaviour. In parallel to the development of an analogical test, an algorithm was developed to transpose the 3D solids of the digital model into simple geometric elements such as lines and planes useful for the definition of the various processing stages.
Through the direct connection between the parametric model and the manufacturing tool, Robot KuKa KR-150, the various stages of the manufacturing process have been determined such as "picking", "cutting", "drilling" and "stacking" (Figure 4). At the end of the production process, we assembled 940 wooden rods of variable size in 8 arches divided into 16 parts with 35 hours of production. The construction of the robotic Fusta Robòtica prototype expressed the potential of digital fabrication with a non-industrial setting able to materialize the formal generation through the assembly of simple, irregular and low-engineered wooden rods.

1. Fusta Robotics was developed within dell'OTF, Open ThesisFabrication, professional program post - graduate disbursed by IAAC, Institute of Advanced Architecture of Catalonia.

Digital Urban Orchard: form follows data flow

The Digital Urban Orchard[2] prototype is the result of an applied research program whose goal is the design and the realization of a functional prototype at full scale to be implemented in urban public spaces. The criteria relating to material, functional, structural and environmental performance have been taken to inform the generative computational process later materialized through robotic assisted manufacturing and manual assembly process. Made from 1,681 wooden rods and 52 hours of production through a robotic manufacturing process and manual assembly, the pavilion hosts a hydroponic cultivation system and an adaptive silicone skin (currently under construction) able to ensure the indoor comfort conditions that are essential for the plants growth. The commingling amongst form, location and function has required a manifold responsiveness able to ensure proper compliance with the performance required by each of the individual parameters listed above in relation to the urban environment where it was subsequently assembled and placed. The formal generation, as well as the production process, is informed by a series of data coming from environmental analyses able to provide a

2. Digital Urban Orchard was developed within dell'OTF, Open ThesisFabrication, professional program post - graduate disbursed by IAAC, Institute of Advanced Architecture of Catalonia

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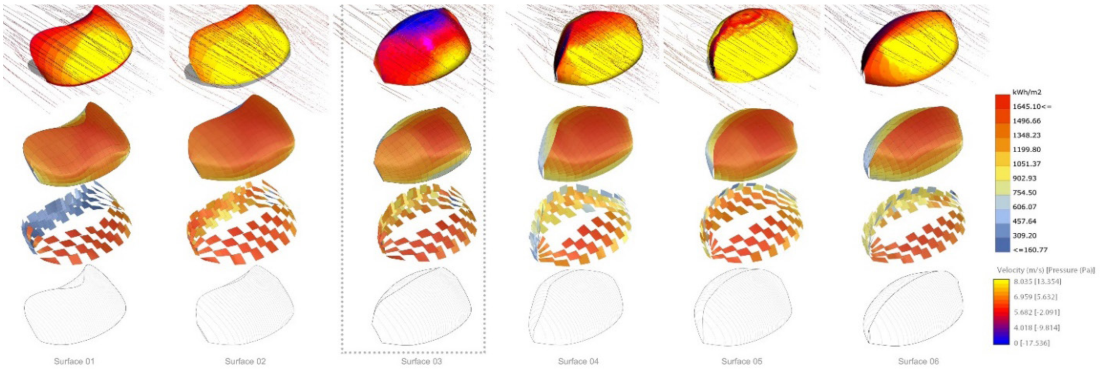

Figure 5.
Digital Urban Orchard. Shape catalogue: six different configurations resulting from the optimization. Surface 03 results as the final design choice because of the aerodynamic shape, of its global shape's solar access and of plots best orientation according to radiation values.

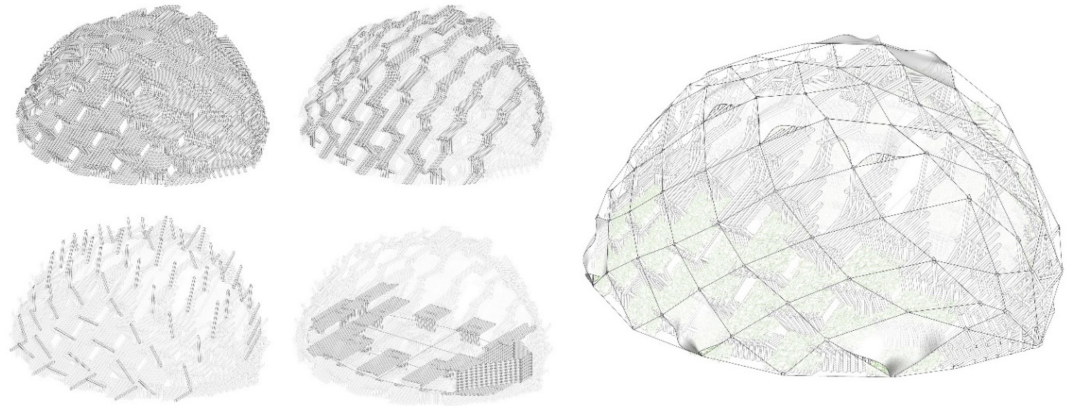

Figure 6.
Digital Urban Orchard. Structure Components: main trusses, skin holders, furniture elements and the final configuration.

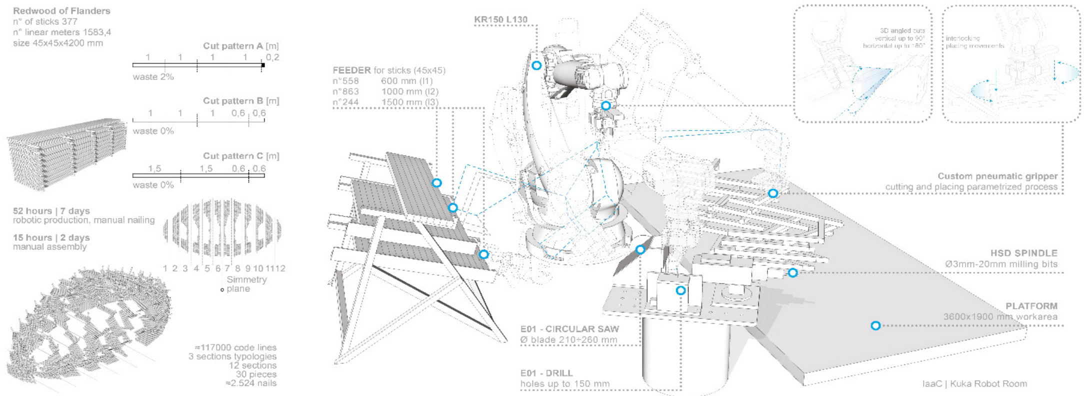

Figure 7.
Digital Urban Orchard. Statistics and Robot Room setup.

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proper climate reading of the context, from the material used and the structural system.

Thanks to the computational process, the meta-design is developed through the definition and analysis of a catalogue of solutions, a possibility space that made it possible to optimize the shape among different performance criteria in order to define a responsive architecture that is the result of a mediation between the creative process and the performance-based optimization. The final form was selected from a catalogue of solutions. The solutions are the result of a process informed by the maximum size of the wooden rods in relation to the adopted production methodology and the available tools, by a range of possible angles used to cut the ends of the rods and by a series of conducted environmental analysis, more specifically CFD analysis and solar radiation. The CFD analysis allowed minimizing the wind pressure on the outer surface of the pavilion in order to ensure the structural balance while the analysis of the solar radiation has allowed determining the inclination of the wooden rods hosting the hydroponic system.

The final responsive shape has been discretized through a series of sections: 6 types for a total of 12 sections. In relation to the size of the sections and the working platform, we defined three manufacturing strategies that provide for the construction of the entire section or for the assembling of two or three parts of the final section, for a total of 30 parts assembled. The adopted structural principles are the same used in the pavilion Fusta Robòtica. The structural hyperstatic pattern based on the optimization of the material generated by the alternation between diagonals and elements able to ensure structural rigidity has been developed with a support system for the hydroponic plant, for the silicone skin and with furnishing objects that are functional to the space. To maximize the resistant section we used 2,524 nails in nailed joints with a collaborative process between manufacturing robotic and manual finishing. The structural analysis conducted on a typical section under various load conditions has allowed validating the structural choice made despite showing a high displacement due to the horizontal pressure of the wind in the extreme conditions as set forth by the legislation.

The implementations have been possible thanks to the end effector customization used for the production, the industrial gripper, and some tools used for the production such as the circular saw and the wooden rods dispenser. By analysing the experience previously carried out with the pavilion Fusta

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Robòtica, the production process has been implemented in all its phases of picking, cutting and stacking in order to reduce the material consumption (reducing the material waste to only 2%) and create an additional value to the production process. The formal outcome, the result of 52 hours of production with Kuka KR-150 robot and 24 hours of manual assembly coming from the information of the process and the optimization of the performance, has been completed in a production process that can control the complexity and transform it into design opportunities while ensuring rapid execution and automation. The creation of a customized digital process, rather than a product, allows making the prototype an open source through the spread of the digital model that can be customized with the information coming from the specific application context. Hence, the output will be a responsive process able to vary the morphology compared to the specific relationship among shape, context and function.

In.Flux: structural optimization and new material system for responsive architecture

The scale 1: 1 prototype In.Flux[3] represents the physical transposition of an informed design methodology in which data relating to material, structure and manufacture have determine the final morphology through a form-finding process. Through the construction of the prototype by the size of 4 meters in length and 2.2 meters in height, made of 0.75 cubic meters of high-strength concrete and 8 blocks of EPS in 1080 hours of processing, an operational methodology has combined digital computing, material testing and robotic manufacturing. The proposed operating methodology has provided the definition of a meta-design in which the start-up geometric parameters, as well as the material and the production method chosen for the realization of the prototype were made explicit. Thanks to digital computing and the construction of a flexible model (Davis 2011), the structural analysis conducted was used not only to verify of the performance among codes or regulatory aspects, but rather as a generative factor that can inform and expand the possibilities offered by the meta-design. The choice of the material and the manufacturing method, as well as the structural performance, turns out to be data project, input, and not predetermined or superimposed factors as it happens for a top-down approach to the project. The structural analysis and the optimization of the geometric parameters have defined the space of possibilities and the designer is required to make his choices in relation to the project goals. The computational tool allows taking a design strategy informed by data relating to the performance (in the specific case structural data) thanks to the possibility to process

3. The In.Flux prototype was developed as part of AA SummerDLab 2015 workshop held at the Architectural Association in London and Hooke Park in Dorset

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and using a large amount of information, transforming them into design input and elements generating shapes. In the specific case the structural iterative analysis realized by the Karamba® plug-in for Grasshopper® has allowed to define the minimum thickness of the surface in relation to the range of the displacements and identify and generate the openings so as not to interfere with the distribution of loads and unloading of the same in the foundation in relation to the stress line identified in the digital environment. In the realization of the prototype, the role of digital computing has had a dual purpose: the optimization of the structural performance and the simulation of a natural system, agent behaviour, in a digital environment.
The agent-based simulation created by Processing® software was generated starting from the curves division of the openings edge and regulated by defining parameters and values of cohesion, separation and alignment in order to determine the system behaviour. The forces acting in a perpendicular direction with respect to the previously optimized mesh, moving to the Z direction as far as the base, generate a deformation of the mesh that increases the resistant section, particularly near the openings and the base of the system in such a way that it ensures continuity in the vertical distribution of the loads. From the geometric coordinates of the vertices, the mesh necessary to define the morphology of the formwork and generate the files containing the processing paths to be transferred to the robot has been rebuilt.
Thanks to the plug-in Grasshopper © it was possible to reconstruct the mesh starting from a set of geometric information and then subsequently generate the file for the formwork as negatives of the two main surfaces of the wall that have the geometric pattern. The robotic manufacturing process was carried out by using a Kuka KR-150 industrial robot equipped with milling spindle, while the files were transferred to the machine thanks to RobotCam software through which all the parameters related to the subtractive process have been checked. When defining such an approach, the task to respond and adapt to inputs coming from the outside is transferred to the architecture through the definition of geometrical parameters. Responding to inputs via a data - driven process by using them as parameters of the project introduces a new concept of responsiveness and sustainability because each element of the system is only placed where needed. Contrary to the traditional design process, also the production method becomes a design input the designer must take into account to verify the effective constructability.

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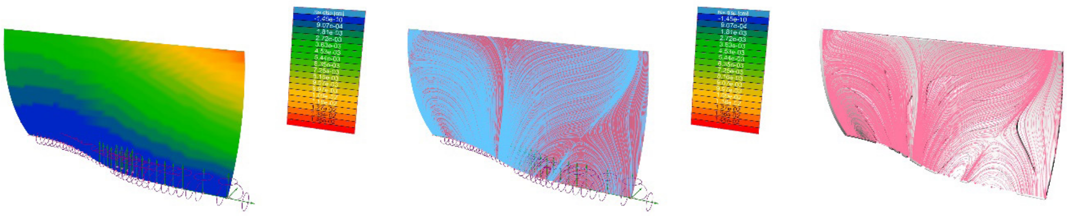

Figure 8.
Shell structure optimization with high-strength concrete (C90/105).

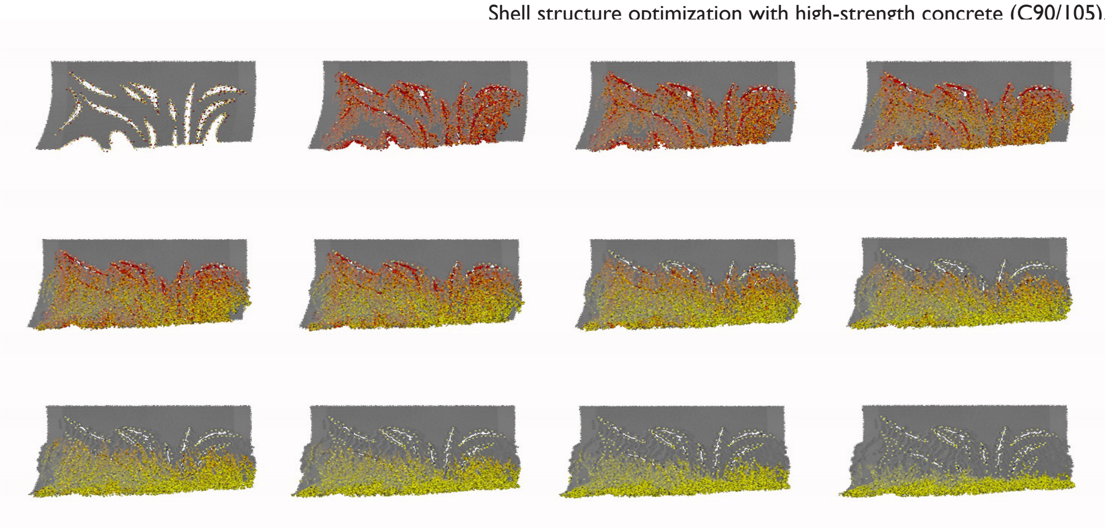

Figure 9.
Agent-based simulation starting from the optimized mesh.

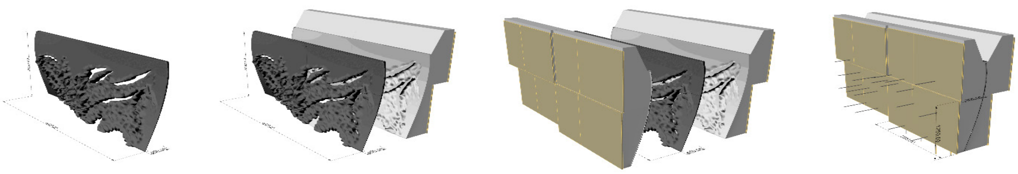

Figure 10.
Simulation of the fabrication process.

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Parameters such as the size of the workspace, the machine type, the type of end effector used and the relationship between the manufacturing method and the material become design variables expanding the space of possibilities. The result of a design methodology that provides the definition of a project goal and the space of possibilities is a responsive architecture that focuses on the process rather than on the tectonics and the final morphology.

Conclusion: define a new concept of responsiveness through data-informed design and complex fabrication techniques

The realization of prototypes has shown the possibility to materialize informed morphologies regarding performative parameters through the direct connection amongst data, flexible digital models (Davis, 2013) and robotic manufacturing. More, it has proved how to build a customized digital process able to convert complex geometries into simple geometric elements and develop an efficient manufacturing process. The raw material for Fusta Robotics as well as the complex relationship form-context-function of the Digital Urban Orchard pavilion and the structural performance of InFlux represent design inputs that generate informed architectures whose morphology is the result of the optimization of performance parameters that are objectively measurable. Architectures that can be materialized through new digital manufacturing technologies able to ensure freedom and complexity of execution with no industrial settings and not using engineered materials that are locally available. The proposed methodology reverses the mass production paradigm by introducing a new digital aesthetic where the customization of the form is interrelated with performative parameters and a material intelligence that emerges from the computational process. The continuous flow of information between design and manufacturing becomes relevant in the management of digital forms in order to start the following process of materialization. The concept of file-to-factory is enriched with new meanings beyond the dichotomy between digital file and production industrial process.

This is possible thanks to the democratization of the machines, the result of the third industrial revolution, and the possibility of decentralizing the production. With the post-industrial process, what changes is the direct relationship with digital manufacturing tools able to share and occupy the same space of the designer and to become an extension of it (Kohler 2014) in the workspace. The designer acquires a new material sensitivity and takes care of the entire design process from the concept to the construction, from an object-oriented approach to a process-oriented material approach called critical making (Ratto 2011). Starting from this scenario, future developments include the introduction of a further performative layer able to give the machine decision-making skills through the development of a system for real-time relationships between the virtual space of the digital and physical model. The design of adaptive models, able to vary in relation to the production process, allows reducing all problems related to tolerances and makes the robotics manufacturing even more efficient. The direct connection between digital and real space, guaranteed by the use of robots, eliminates process abstraction and create a new digital culture developing an aesthetic and material sense together with a social and cultural dimension. In summary, there's a post-digital era based on the performative customization of architecture and a new material sensitivity through the new computing and digital fabrication technologies.

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Integrated evolutionary strategies on structurally informed complex grid morphologies

Katerina Saraptzian // AUTh

Abstract

This paper is attempting to present an on-going research investigation performed on a PhD level, which addresses the notion of algorithmic thinking in architectural design that can re-create efficient integrated design strategies. It focuses, in particular, on the notion of structural complexity and attempts to interpret it as a 'bottom-up' property that can inspire and facilitate the design of non-standard forms in architecture. This is primarily observed through an evolutionary procedure that informs and transforms in a recursive manner the form-finding process and fosters the emergence of complex bio-inspired architectural forms, with particular interest in the case of irregular grid structures.

The investigation is taking into account theoretical approaches, as well as bio-inspired paradigms that excerpt self-organizational procedures in the determination of the morphological process and is performed through the research method of digital experimentation. More specifically, the experimental approach attempts to investigate a series of parameters that can dynamically affect the form-finding procedure of an irregular grid system and aims to generate evolutionary strategies on structurally informed complex morphologies. The informative parameters include the determination of specific geometrical shapes, the subdivision type of distinct irregular grids that are bio-inspired by natural structural patterns, the present dynamical possibilities and finally the mechanical properties of the material composing a structural form.

Conclusively, those parameters are examined through their combination on a set of digital simulations, while the whole process is being computationally encoded and performed within the environment of Grasshopper.

Keywords

'bottom-up'; Grasshopper; bio-inspired paradigms; design strategies; evolutionary; parameter; digital simulation.

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Background

Presently, we may observe a “digital shift” in the architectural practice. New principles are embedded with the ongoing architectural theory enhancing the idea of form and structure with terms like complexity, complex theories, dynamical systems, non-linearity, non-standard, digital tectonics, leading to a hybrid perception of the architectural discourse. These new confrontations have received from extent enthusiasm to severe criticism concerning their possible impact on architecture. We may speak of an impact, not only engaging with the degree of benefits put forward by digital technology on design, but more on the transformations architectural discipline and discourse is starting to follow.
One of the significant events that have led to an alternative way we interpret architectural theory and experience design is the rise of the epistemology of computer science in conjunction with the theory of cybernetics. The appearance of the Alan’s Turing “algorithm” and in turn gradually to “algorithmic design” (Terzidis, 2006) constitutes in fact a conceptual evolution in architecture, leading to a new state of thought and design, that of ruled-based relational thinking. Form and design is now generated under the co-existence of a relational system and rules that define it, being not singular and static, but multiple and dynamic. We may speak of technological artifacts that were not seen only as a means of executing commands, but also as digital entities that could produce data, relationships and ideas (Parisi, 2013). Moreover, terms such self-organization, as part of a complex system and a key concept, plays another important role in design, trying to give a further explanation to the inner organization, with concepts such as inner dynamics and constant evolution (Karabaj, K, 2006).

This in fact triggered questions such as the relation between scale and tectonics(Pico, 2010), form and structure and the way they interpolate in design. Beliefs such A. Picon’s reflects a paradoxical effects on the transition between the screen and reality, with famous examples, such as the Mediatheque or Frank Gehry’s projects being impressive and ornamental form expressions, but giving at the same time little regard to any structural restraints they entailed. Nevertheless, we may observe the emergence of a “new materiality” that has influenced the conventional structural constraints followed before the advent of computational era. Regardless if the structural parameter was at a secondary stage in the design process, it has undoubtedly challenged the norms towards a new attitude in the technological techniques that would perform such revolutionary geometries. This has identified initiatives, such as the “informal” of Cecil Balmond (Baldmon, 2007) and Greg Lynn “animate form” (Lynn, 2011) that attempt to give this alternative dimension of a structural expression in the morphological generation.
On the other hand, biological paradigms and the recent investigations on several natural structural patterns have become living examples towards this direction. We may observe several natural constructions that are examples of self-organization systems and products of evolutionary processes that incorporate dynamical parameters. The most representative example is the microstructure of the cancellous bone that reflects this adaptation in both tensional and compressional forces as seen in the figure previously (figure 2). Specifically, the microporous inner system re-adapts its cohesion and thickness according to the external stimuli that take place (Weinstock, 2006).

Simulation procedure: description and implementation

<u>Main description</u>

This “new materiality” confronted by the digital architecture along with several bio-inspired examples that indicate the ability to adapt to severe stress conditions and self-organize into a more stable organizational system as mentioned and observed in biological examples, can re-generate design

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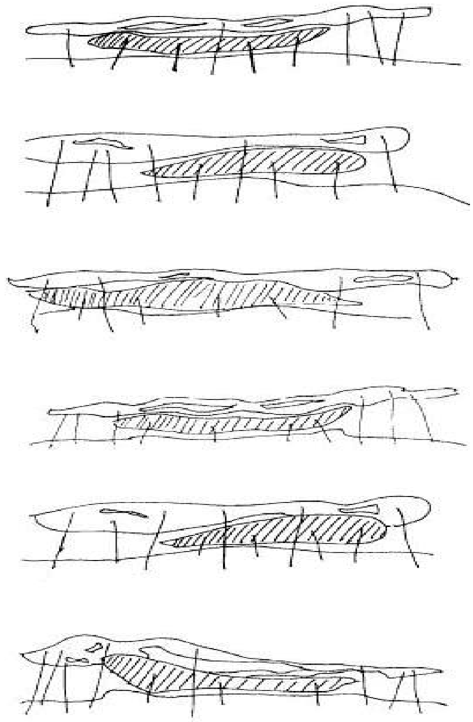

Figure 1.
Cecil's Balmond Sketches on Chemitz Stadium, ("Structure and The Informal", 1997)

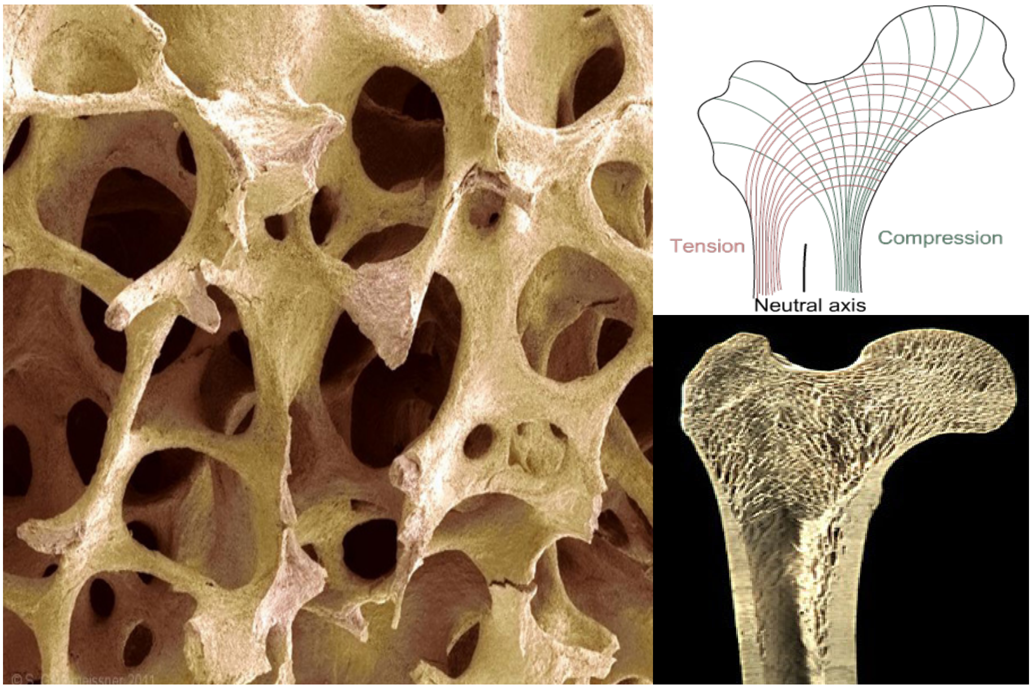

Figure 2.
The microporous system of a bone's inner structure generated according to external loading conditions

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strategies. These strategies may have the capacity to respond to the changing built environment and be optimized accordingly, such as optimization procedures and evolutionary algorithms. When referring to architectural form and materiality, those concepts of adaptation and self-organization are transforming their external reference factor to a building's conditional system. Loading conditions, such as gravity, wind, lateral, and live loads, thermal and earthquake loads shall be taking place, whilst the way that material, form, and structure are organized becomes important too.
Therefore, we may investigate on and form morphological processes in architecture that will be able to respond to the present structural challenges and constraints using at the same time the digital tools offered by the recent technological advancements. This process is what this research is mainly investigating and can be described and divided into three main stages. The first stage includes the geometrical generation of an irregular grid, the second one informs with structural elements and real cases loading scenarios the whole model and while the third ones evolves and adapts the model by using self-organization processes. This is performed in a recursive manner and converges when reaching an equilibrium point.

Computational Environment and Language

The whole procedure was established through the computation-friendly environment of Grasshopper. Grasshopper (www.grasshopper.com) is a very popular program used in architectural design that gives the opportunity to engage with the geometry parametrically. Developed as a built-in plugin for the design program Rhino 3d, it gives the opportunity to visually program/compute a design process, with limitless potentials. Moreover, structural analysis programs were necessary that could perform a structural evaluation, therefore, since the whole process intends to function in a recursive way, Karamba plug-in (www.karamba3d.com), an extension of Grasshopper, would serve as the structural analysis aid tool that can be combined in a parametric manner. Particularly, Karamba is able to assist with a number of functions that can calculate, assess and analyze the structural performance on a variety of geometries, from grids to shells structures. It can also provide the opportunity to evaluate any structure under a number of feasible conditions, such as gravity load or even temperature effects.

Non-standards Structures and the definition of irregular Grids

The investigation was mainly focused in defining the generation of non-standard grid morphologies. Thus an attempt to understand their generation process as well their formal representation was also necessary.
We may observe a number of distinct non-standard structures, such as pneumatic, tensegrity, lattice structures and many more (Coenders, 2003). However, a further scrutiny shall be made on the case of grids, with special reference and interest on the irregular grids and their structural behaviour as a self-supporting system while re-define them through their distinction via their generative technique. Among the techniques that generate grid structures, whether these may refer to regular or irregular- ones, is the utilization of "tiling and packing" or "tessellation" technique. Tessellation is a method that accounts for its potentiality of subdividing space with the less or zero number of remaining unused areas. Specifically, it is a structural arrangement of inherent geometrical stability that finds expression in two (2) or three (3) - dimensional space. Additionally, de-

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signer such as Lisa Iwamoto defines tessellation as a means of more close to fabricational patterning through a "collection of pieces that fit together without gaps to form a plane or a surface (Iwamoto, 2009). However, the research interest focuses in tessellation as a structural pattern utilization that is a pattern structurally stable and arranged in that way of offering self-supporting structures, as firstly applied by Buckminster Fuller. Thus, we shall take a short presentation of the types of tessellations, as well as the recent and more alternatives ways that have emerged through computation.

There are many alternatives of subdividing or tessellating space, such as regular tessellation, with standardized joints and member lengths. We may account for regular tessellation, that uses three main shapes and semi-regular tessellation with combinations of the above. Recently, contemporary architecture has started to explore the adoption of more recent mathematical inventions mainly influenced by the biological paradigm, including aperiodic tiling, patterns that have smaller in number or repeated units, but whose arrangements are such that the resulting patterns, unlike orthogonal or hexagonal grids, cannot be superimposed upon themselves through translation(Burry, 2010).. A very interesting perspective is the interpretation of Farshid Moussavi in the "Function of Form". These systems of grid distortion or variation, as mentioned by Moussavi, are an approach of transversal system, in terms of a system of cross sections with distinct topological variation (Pearce, 1990; Coenders, 2003). Because the base unit is not geometrically fixed, it may constantly vary and mutate when hybridized with other units, into novel and unpredictable forms that are spatially specific and capable at the time to adapt to external concerns. In other words, we may see a hybrid way of approach to a "non-standard" design that takes into account a bottom-up approach, from the properties of the system to the influence and performance of the whole. She also observed and made a relevant table with how a system, in terms of surface, dome, folded plates, shells etc, in accordance with a certain tessellation can have a variety of affects and effects in architectural form and structure. This may imply the numerous capabilities and complex behavior on this area of grid distortion research may offer.

These biomorphic and natural processes of subdividing space shall be generated by the use of a number of mathematical and computational three-dimensional representation, such as Delaunay triangulation, Dirinclet or Voronoi tessellations, Weairie-Phelan foam structure, Catmull-Clark subdivision, etc

<u>Importing dynamical and structural factors</u>

The next stage is to present how the model was informed with dynamical parameters and the structural evaluation procedure. A typical simulation of a structural analysis performance, requires a number of input elements. In other words, in order to generate a correct and valid structural model, it is necessary to indicate what is the current material and support locations, for it to become rigid and to have certain limitations in movement, and finally to set the preferable loading condition. This information is usually necessary to almost every evaluation or simulation program on structural analysis. The model, thus, must be translated into a model than can be identified by Grasshopper and Karamba3d. Therefore, one of the first steps is to indicate what are the elements that compose this particular structure. There are two basic categories of structures that Karamba is making as a distinction. That is beam (grid) structures (or trusses) and shell structures. We shall interpret our structures as those that consist of beams and nodes, which is a grid structure.

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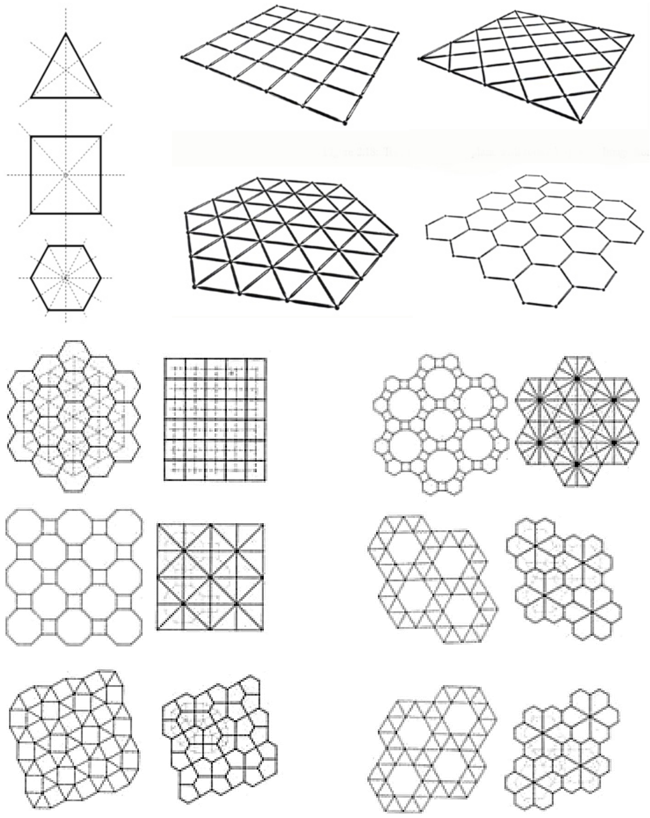

Figure 3
Regular and Semi-regular plane tessellations
Source: Meijer J.H. and Coenders J.L., 2007

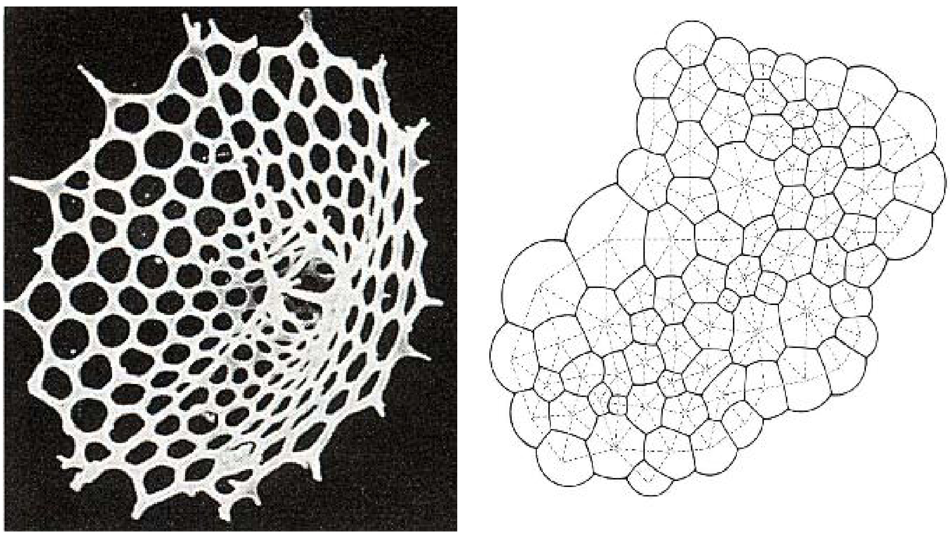

Figure 4.
Soap bubbles Array
Source: Left (Pearce, 1990) and Radiolara Shape right (Coenders, 2003)

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At first, we shall transform the grid network, that for the moment is only consisted of a compound of points and curves, to a translation set of beams and nodes systems. It is also necessary to indicate the intersected points, or (or nodes) between the curves and to set the element type to beam. Karamba is able to provide with a list of possible loads that are engaged in a typical structure. This is performed through the indication of a load type or a combination of load types acting together. Several types were considered that were chosen in relation with the evaluated geometry. Thus, most of the cases were considered to subjected to the following load combinations (Figure 6):

- Dead loads; -Live loads; -Wind loads (lateral forces); -Snow loads

Another information is the determination of the support locations. If closely noticed, we may observe that our structure should have its support locations only in the areas where it touches to the ground, or in other words when it is in contact with the 0 value in the z-axis. Therefore, all these points were extracted and provided in the support component of Karamba among with certain limitations in Rotation and Movement.
Since all the information is collected, now it is possible to proceed to the evaluation and assessment of the structural model. The assembled model is analysed and in turn computes some useful output information, such as total displacement, total mass in kg and Energy. The structural analysis method is mainly based on the first order theory (I), in order to compute a structural model behaviour.

Encoding self-organization into computational architectural design

Those biological models and material structural patterns have opened new possibilities for interesting morphological paradigms and advanced architectural design in computational architecture. They have informed several mathematical inventions, inspired digital techniques and can become the basis for physical investigations and digital simulations for new morphogenetic models in architecture. Moreover, this ability of material systems to adapt to severe stress conditions and self-organize into a more stable organizational system, can generate design techniques and advanced digital tools, such as optimization procedures, form finding and evolutionary algorithms, based on natural evolution.
Thus, it is important to make a relative comparison between the ideas behind natural evolution and adaptation, and those fostering computational ideas, such as optimization, form-finding and particularly structural optimization, and how those ideas have inspired and developed concepts in engineering and architecture.
As already mentioned in the previous paragraphs, computation is a mean of exploiting and investigating non-standard structures, as they entail extremely complex mathematical equations. Moreover, computation apart from its ability for advanced geometrical representation, it has also developed the ability of forms to self-adapt in certain restrictions and external loading conditions. This process is widely known in computational theory and practice as optimization.
In our case, the utilization of Galapagos plug-in gives us the opportunity to perform an evolutionary process through genetic algorithms. The basic steps to proceed to such process is to define the genes that will be taking into account and mutated, or in more simple words, diversified, and to define a fitness function, that is the number or mathematical function that will be maximized or minimized.
In this research investigation, the genome or genes are defined as the space generation of the initial set of points, therefore, the algorithms will attempt to search for different coordination values in order to locate the best combination of points in the specified design space.

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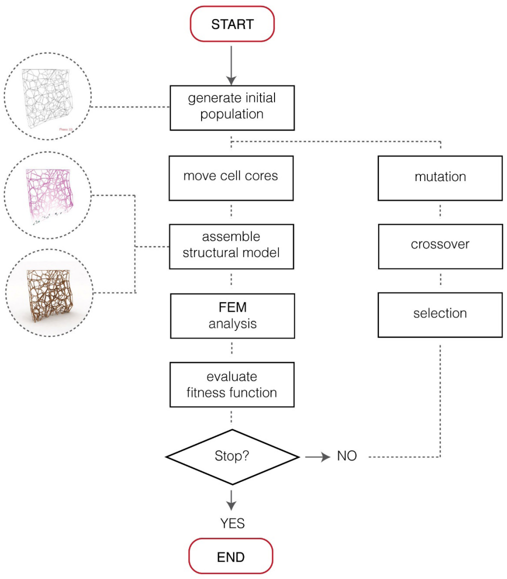

Figure 5.
Load combinations applied during the evaluation

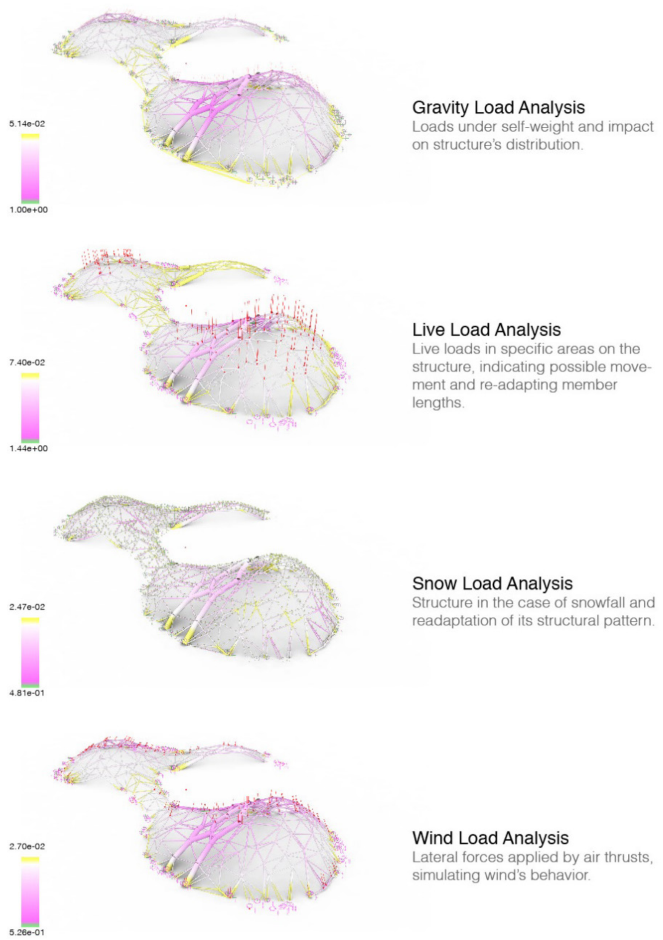

Figure 6.
Load combinations applied during the evaluation

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Defining an optimization goal - Fitness Function

One of the primary goals before formulating an evolutionary approach on a form-finding procedure is to indicate an optimization goal, or in other words a fitness function. Fitness functions are amongst the most important parts on performing an optimization process, as it represents the ultimate goal the optimization seeks to achieve. For example, in structural optimization the goal is to have efficient structures. Efficiency in structural design is translated as a combination between less material and maximum stiffness. Although computer is the one that comes up with the final design, it is the human designer who has to design the fitness function. If the function is designed vaguely or invalid, the algorithm will either converge on an inappropriate solution, or will have difficulty converging at all. Moreover, the fitness function must not only correlate closely with the designer's goal, it must also be computed quickly. Speed of execution is very important, as a typical genetic algorithm must be iterated many times in order to produce a usable result for a non-trivial problem.
However, in our case, the goal is slightly different. The fitness function must be formed as a combination between two objectives, Total mass and Displacement. This can be illustrated in the mathematical function below.

$$\min f(x)=\sum^{n}_{(i=0)} \sqrt{((Dis_i * Mass_i)/n)}$$

This could be performed by either constructing a function that involves both of these figures, or either by using the Pareto frontier via an evolutionary approach, that can give a series of possible solutions covering the "Pareto curve".

Preliminary work & experiments

Some preliminary work during this research has been performed. This included a series of initial experiments in order to develop and specify a design strategy. The process included some basic research in structural patterns and their behaviour and in a next step, some further and more complex investigation on defining and generating this strategy in non-standard complex morphological geometries.
A random blob geometry was initially selected, which was later undergone to several and multiple evolutionary transformations that affected the structural grid configuration. Genetic algorithms were imported as a self-organization technique. Several experiments included the application of gravity loads in combination to random lateral forces in order to investigate the response and self-adaptation of the geometrical organization, as seen in the results by the evolutionary process in the figure below (figure 7).

The experiments were evaluated through the resulting of total mass and displacement and their evolution during the different experiments and thus optimized through the course of generations of the genetic algorithmic process.

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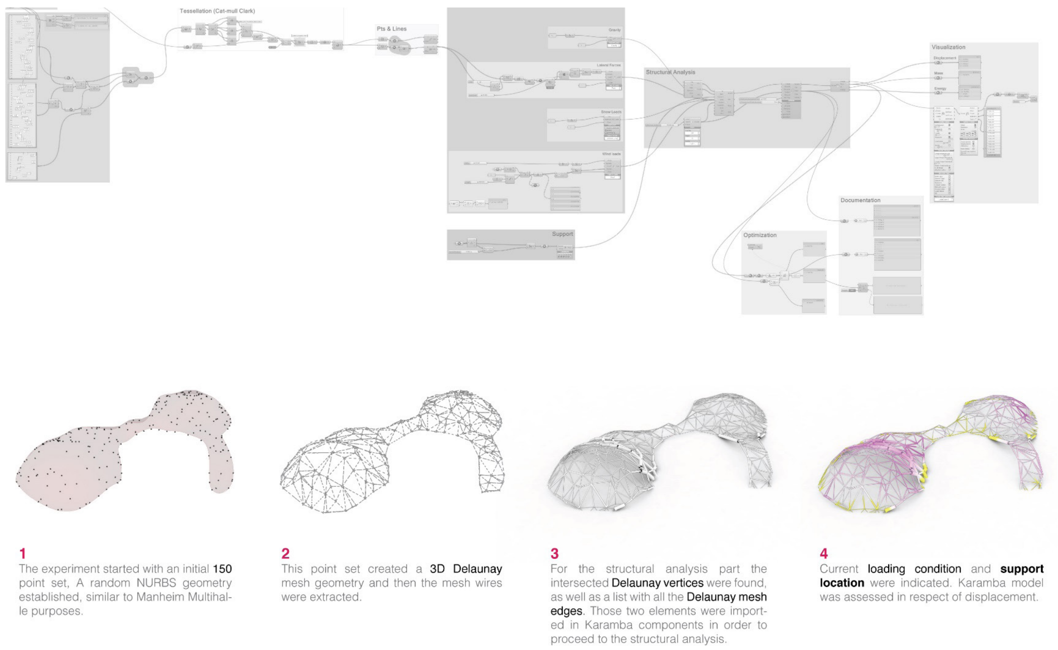

Figure 7.
Generative process un relation with Grasshopper code.

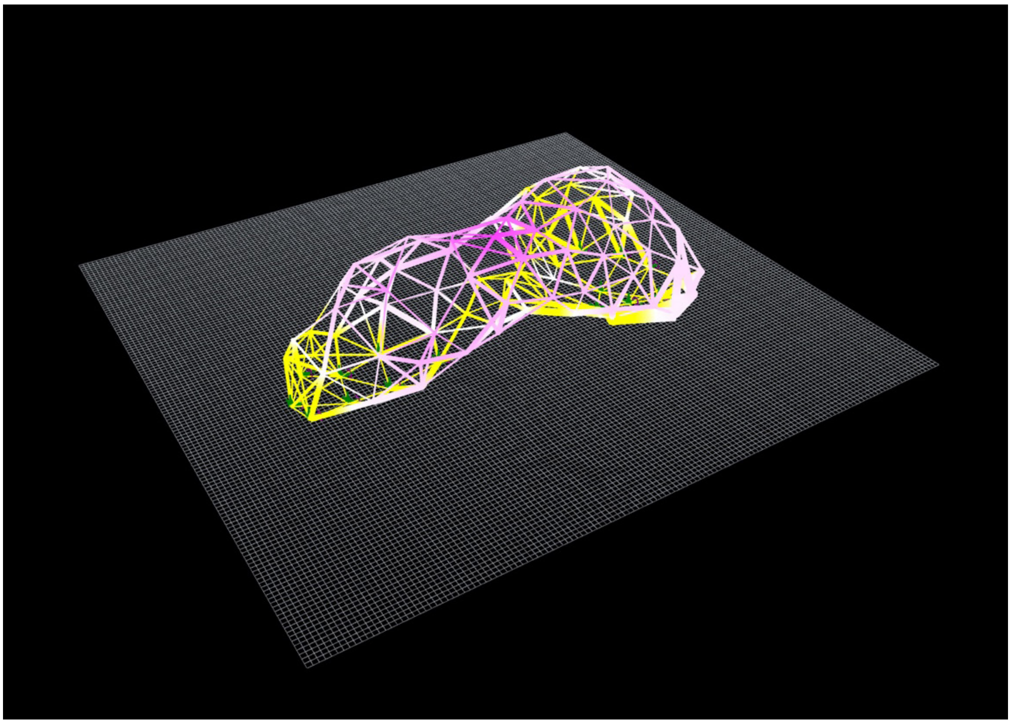

Figure 8.
Simulation process during the preliminary process of an evolved geometry

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Simulation demonstration

Case Study 01: Wide-span NURBS surface

The first simulation is examining the paradigm of Manheim Multihalle in Germany as a load-bearing geometrical shape with specific characteristics in terms of stability. This particular example acts as a sheltering, covering, wide span geometry, concentrating all the loads to the perimeter of its shape. This morphology has 3 out of 4 loading conditions in present, and in particular it is subjected, apart from self-weight, to wind and snow loads. It is being investigated in all three subdivisions, while adapting and optimizing the bar diameter, sizing and thickness, depending on the current stresses on each of those elements. The whole configuration is structurally evolved, using evolutionary algorithms, such as genetic algorithms, which have the ability to combine and solve multi-parameter problems. This particular example is structurally evolved in adapting the grid configuration and relocating the generation points of this grid, with criterion (fitness function) less deflections in combination with less material (lightweight). Regarding the material, steel is in default.

Case Study 02: High-rise grid morphologies

The second simulation involves structurally evolved morphologies on a typical high-rise volume. Therefore, the experiment is focusing in the adaptation of the three grid configurations, in order to observe the effects that exhibits on the volume morphologically. The examination is realized both in a shell and a volumetric spread of points, resulting to grid-shells and three-dimensional grids respectively. A typical high-rise volume is mainly subjected in wind and live loads, which is in direct contact with the kind of uses it is designed for. Beam thickness is also optimized and grid formations are genetically evolved in both less deflections in combination with less material (Figure 12).

Material-based grid morphologies

The third and final simulation is experimenting in material-based grid morphologies that are adapted and evolved structurally. The initial geometry does not rely on a specified geometrical shape, but on a random NURBS curved geometry. Four (4) different materials are chosen (Figure 13), that have distinctive mechanical properties and resilience in stress and other forces, such as steel, wood, aluminium and concrete. The goal is to inform, through those properties and stress characteristics, the curvature of the surface by changing the control points, and determination of support locations, while adapting the configuration of grid generation point. The prevailing loading conditions is only based in gravity loads, while the optimization procedure is evaluating the structure under less deflections.

Discussion

In conclusion, this paper aims to present the development of effective algorithmically-based design mechanisms that enable and facilitate the design of non-standard forms exhibiting structural complexity. In particular, structural complexity is addressed as an integrated, bottom-up property that is able to affect dynamically the form-finding process of irregular grid structures. A number of digital simulations were conducted in order to form a performance-oriented design process focusing on structural efficiency.

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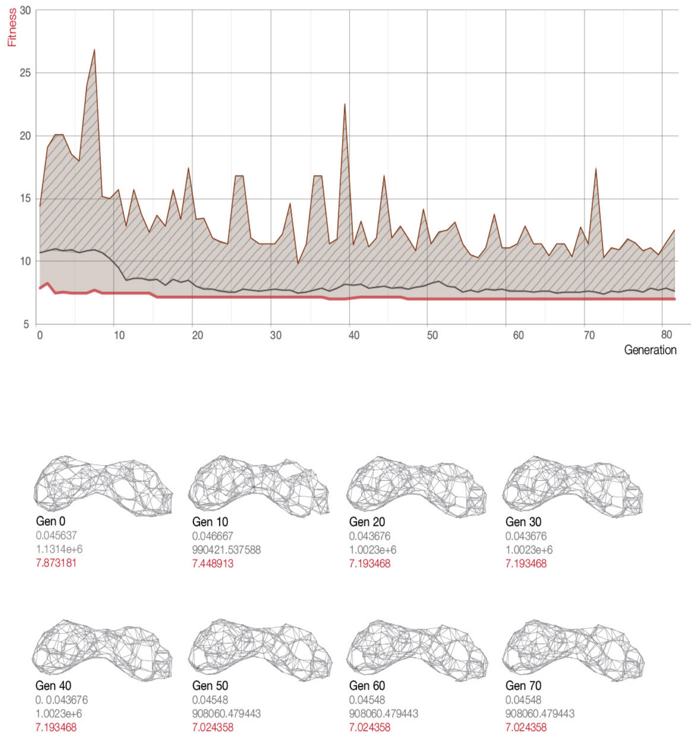

Figure 9.
Course of fitness function and resulted geometry every 10 generations in the genetic algorithm.

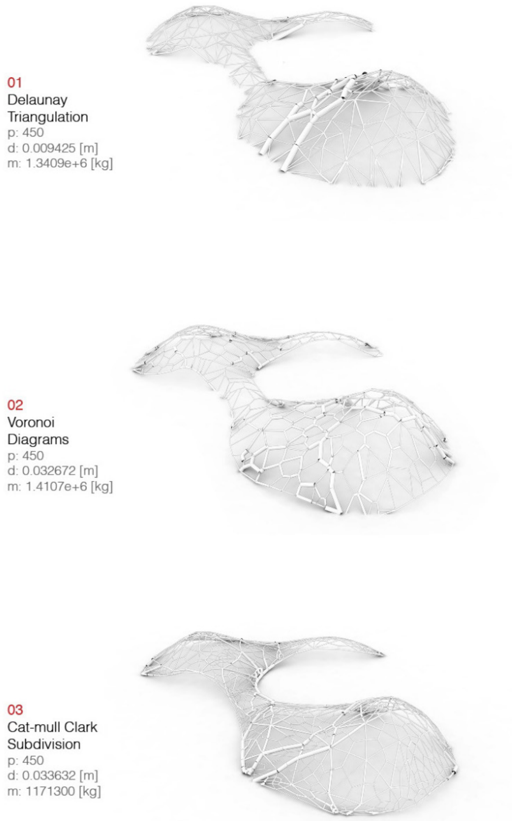

Figure 10.
Samples of several evolved irregular grid morphologies

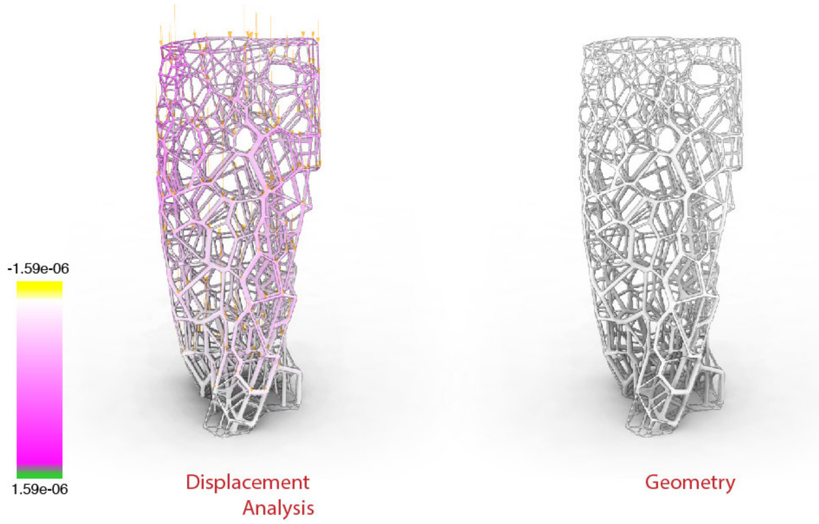

Figure 11.
Displacement evaluation and final geometry of a high-rise morphology.

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The research intents to adhere a holistic approach in relation with the subject of interest, examining all the possible loading conditions and formal applications in order to reach and form solid results. This can enhance architectural process with a valuable design strategy that can affect more efficiently the final design result.

Several conclusions can be extracted during the research process that could offer a valuable contribution to knowledge through their arrangement on three main directions. The first direction is conclusions in terms of architecture, which includes some observations and formal evaluations of the resulted morphologies, such as light, ventilation, aesthetics, as well as possible architectural uses that those grid morphologies may have.

The second direction are conclusions regarding the structural effectiveness of those forms, in terms of structural stability and rigidity. The deflection values in each case are compared in order to reach some conclusions. The third direction is towards the computational method of the evolutionary algorithms. The values examined are the time of convergence (optimum form) and comparison between genetic algorithms and simulated annealing as appropriate computational method in design.

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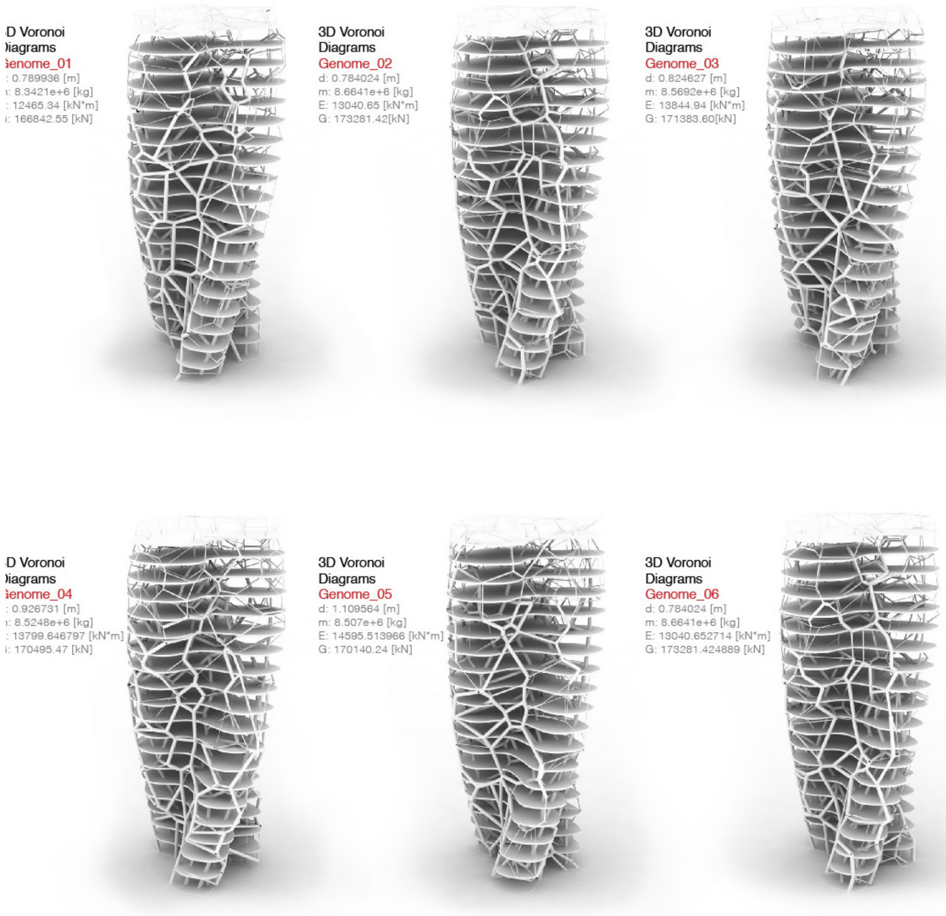

Figure 12.
Various samples on a volumetric Voronoi grid configuration

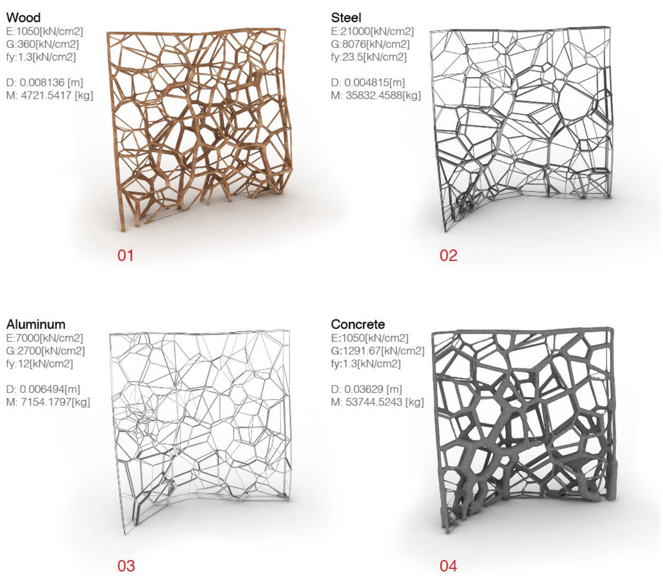

Figure 13.
Samples of material-based grid morphologies based on Voronoi diagram pattern.

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Deployable Arches Based on Regular Polygon Geometry

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Abstract

This paper discusses a deployable-arch-structure design that is built using articulated bars, commonly called a scissor-system, and is based on the regular polygon geometry.
The deployed-arch shape can be determined by inscribing regular polygon geometry in a circle. It is defined by the: a. number of bars required, b. position of the pivots, c. pivot-point distances, d. bar length, and e. open-geometry angle of the arches.
The goal is a deployable half dome made up of semi-arches. Traditional arch construction depends on external structures to provide stability until the keystone is set, which then allows the supports to removed. Deployable structures avoid the need for these external supports greatly simplifying the assembly process and deployment time.

Keywords

Deployable scissor structure, folding structure, portable, arches, regular polygons, dome, transformable architecture.

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Precedents

Geometry Definitions

Scissors are generally defined by two bars or articulated panels joined at a symmetrical (central) or asymmetrical (eccentric) point. This forms a two-dimensional scissor (figure 1) although it is perfectly viable to form three-dimensional scissors with multiple bars forming scissors groups from triangular prisms (figure 2), quadrangular prisms, and regular polyhedrons (figure 3) (Candela, Pérez, Calatrava, Escrig y Pérez, 1993).

The scissor hinge allows for rotation of one element in relation to another without them separating (Candela et al., 1993). The combined movement of the scissor groups in two- or three-dimensional networks results in a variety of deployable geometric configurations. (Figures 4, 5)

Scissor systems allow hinges to be deployed in both linear and curved forms. This research focuses on using two-dimensional scissor systems to generate curved surfaces and explores various possibilities to configure them into deployable three-dimensional domes.

Two curvature types, depending on bar geometry, are possible:

- Constant Curvature

To obtain a constant curve, deployment is achieved with angled scissors along with hinges that have a pivot angle not equal to 180 degrees.

A bar group of equal angles generates rings with a concentric deployment (figure 7)

- Variable Curvature

To obtain a variable curve, deployment is achieved with straight scissors and hinges placed in a straight line. The central hinge is positioned at an asymmetric distance and must comply with the following equation for a correct folding:

$$a + b = c + d$$

This paper does not go in depth on angled scissors. The emphasis is on deployable scissor systems assembled formed from straight bars that result in deployable arches with variable curvatures.

The scissor groups must form symmetrical irregular quadrilaterals (deltoids) and able to be folded. From this, a deployment with variable curvature is obtained. There is also the possibility to form symmetrical diamonds, which results in a linear deployment.(Figure 8)

The following section covers the most common geometric methods used by leading deployable-structure designers to generate curved surfaces.

Perez Piñero method

Emilio Perez Piñero is recognized as a pioneer in the design and application of deployable structures in architecture. Building on Piñero's work, Lina Puertas del Rio created typologies to form spherical surfaces from deployable structures (Puertas, 1989) (Figure 9) including those listed below.

-Square grids: Formed by projecting a grid of squares onto two concentric spherical surfaces with lines starting in one central point and intersecting the vertices of the two parallel planes traced on the surfaces.

-Triangular and rectangular grids: Formed by projecting a square grid onto two concentric spherical surfaces but with the addition of diagonal lines. In this case, the system consists of more and different length bars.

-Equilateral-triangle grids: Formed by tracing equilateral triangles vertices onto spherical surfaces generating the base unit with three scissors, thus achieving greater uniformity between bars. Another method involves using two triangular grids to generate an intermediate spherical surface.

-Equal parts division: The simplest method and is achieved by equally dividing the curves, always starting from a central point and then using scissors in place of the resulting quadrilaterals.

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Deployabl : Arches Based on Regular Polygon Geometry

Figure 1.
Scissor system where movement of the two articulated bars takes place at their center point.

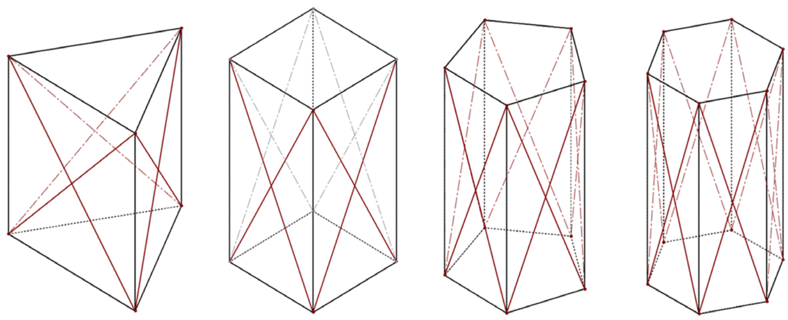

Figure 2.
Folding-module prisms. Based on Escrig's 1984 patent.

Figure 3.
Deployable polyhedrons. Articulated-plane scissor system replace the polyhedron faces.

Figure 4.
Deployable polyhedrons. Articulated-plane scissor system replace the polyhedron faces.

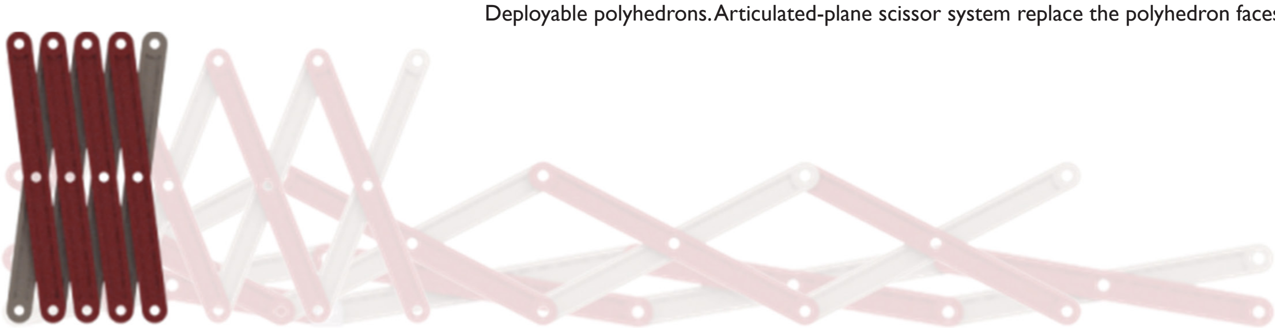

Figure 5.
Configurations

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Escrig's method

This method involves projecting up from a grid onto a spherical surface. The spherical surface is then replaced by bars and hinges to create a scissor-based structure. (Escrig, 2012) (Figure 10)
Similar to Piñero's methodology, Escrig proposed projecting grids onto a generatrix surface, establishing points that can be used to create the structure's shape.
The "C" points are the articulation centre points, or hinges, that are located on the generatrix surface. From a center point, radials are projected so that they intersect with the grid's "D" points. The top and bottom scissor points are located along the radials so that the relation required for structure deployment is realized. (Figure 11)
Another method involves projecting points onto a sphere from an arbitrary focus, which allows for the visualization of the unfolded geometry to be used for dome design. (Figure 12)
Other method is based on regular polyhedron geometry (Escrig, 2012). This example could be used for a portable-pavilion design based on a rhombicuboctahedron and is adaptable as a pavilion or kiosk. The geometry allows for edges to be replaced by scissors, which results in a perfectly folding kit. (Figure 13). A final approach relevant to this research is Escrig's sphere division in parallels and meridians. The images show the angular relation required to guarantee that the scissor units are deployable. (Figure 14)

Gantes method

The Gantes method involves projecting an ellipse that will form the arch axis. By projecting two equidistant ellipses from the first ellipse axis, it is possible to obtain a top surface that can be divided into equal sections (Gantes, 2004).
The base lines originate from the center of the ellipse and intersect with the origin points of the equidistant ellipses. The adjacent segments become the scissor nodes. The scissor angle when fully open determines the width of the arch.
This study proposes equations and a equation-validation method to test the possibility of a deployable arch with both variable-length bars and a variable-surface curvature. These features result in a repeating modular unit that facilitates the assembly process. (Figures 15)

Babaei's research

Babaei's work shows various deployable-arch geometries that are generated using algebraic equations (Babaei, 2009). The illustrated arch typologies result from changing the geometric relation of each successive scissor's inside angle. (Figures 16)

Author's proposal

The current research tries to simplify the manufacturing and assembly processes by proposing a new type of deployable-domed structure. Using simple geometries to determine bar length, these types of structures can be better understood.
This current deployable-arch method uses straight bars to form deltoids. By varying the bar scissor-connection points when creating assemblies, concave or convex arches that form deltoids can be obtained. The key is that the central hole must be offset from the bar midpoint. (Figure 17)
But, how does one determine the optimal asymmetric point to achieve the desired arch curvature? This paper presents a geometric method, based on regular-polygon overlap, to determine hole position. The resulting geometry is made up of regular star-shaped polygons that simulate a scissor grouping. Deployable arches and domes, which are based on a half circles, can be made by rotating the semi-arches.
This geometric method was used in the design and construction of two prototypes. Assembly is

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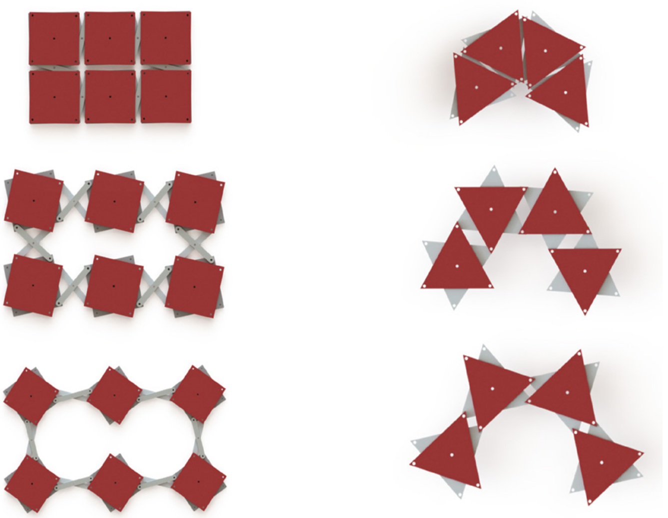

Figure 6.
Configurations

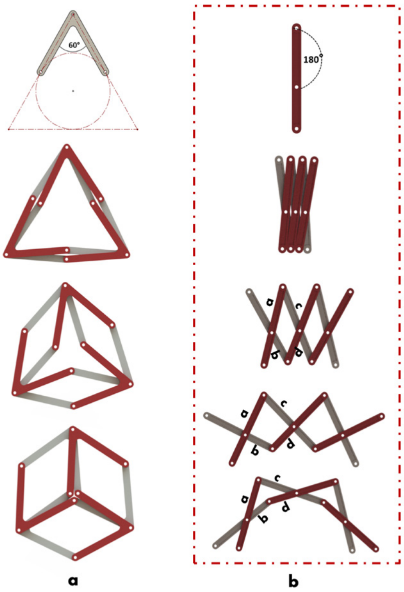

Figure 7.
a) Angled scissors. Equilateral triangle - angle (60°).
b) Straight scissors. Articulated points on a straight line. (180°).

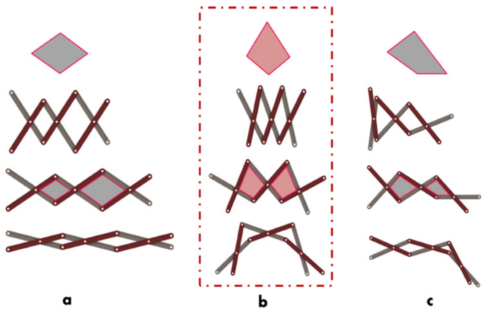

Figure 8.
a) Regular quadrilaterals = linear deployment.
b) Deltoid = variable curvature deployment.
c) Irregular quadrilaterals = can not be folded

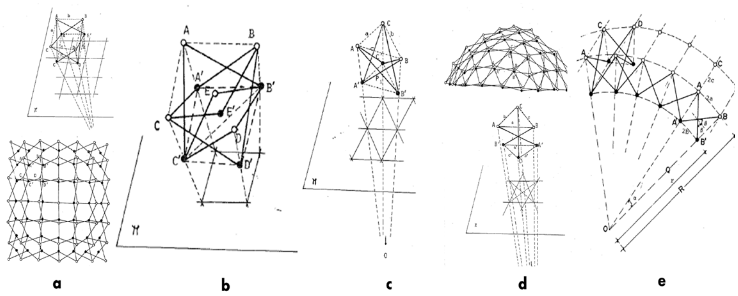

Figure 9.
Piñero's methods. a) Square grids. b) Triangular and rectangular grids. c) Equilateral-triangle grids. d) Double triangular grids. e) Divided into equal parts.
Source: (Puertas, 1989)

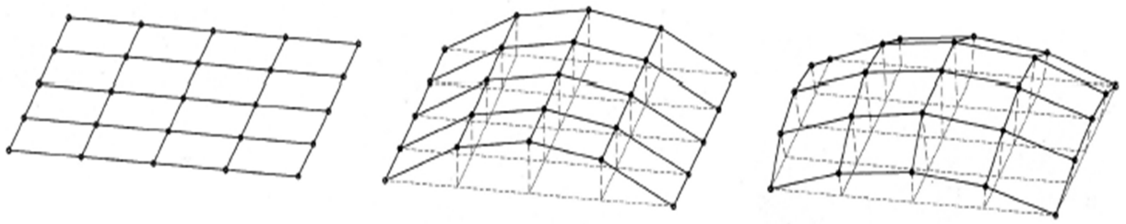

Figure 10.
Square mesh.
Source: (Candela et al., 1993)

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done, much like in traditional arch construction, via manual deployment whereby two semi-arches are simultaneously raised then joined at the top. Once the semi-arches are extended and fastened to the top node, which acts as a type of keystone, the structure becomes stable.
The following section describes the geometric configurations that have been used in this research and details the step-by-step method of how to obtain the different deployable arch geometries. Software analysis and the construction of scale models is used to validate the model.

Geometry definition
The method used to define the deployable-arch geometry is based on geometric patterns. Taking the circle as the geometric regular-polygon base; similar to the technique used in traditional Islamic mosaics applied to decorative elements in walls, ceilings, and doors where their designs are based on geometric patterns.
This technique allows segments based on scissor groups inscribed inside a circle to be visualized and, in this specific case, arches formed by articulated bars to be designed. By setting the diameter, bar lengthand hole position, the desired curvature can be obtained. Some basic values for the different arch configurations are set:

•Six-meter-diameter circles serve as the polygon geometric base.
•Dome height is three meters, which equals the radius of the base.

Steps
The geometry begins with a circle divided into four or more sections. From there, lines are drawn that join the vertices with every other vertex to form two polygons. An example of the step-by-step construction of a polygon, in this case a hexagon:
1. Draw a circle and divide it into the number of desired polygon sides multiplied by two. For our example, a hexagon has six sides: N = 6.
The circle is then divided into 2*N (12) sections. (Figure 18)
2. Connect every second vertex to create the first hexagon. (Figure 19)
3. Connect the remaining vertices to construct the second hexagon. The result is a polygon star formed by two overlapping and rotated hexagons. (Figure 20)
4. Take half the circumference and mark the intersecting points between the sides of the polygons and the radial angles. These points mark the estimated bar length and hole positions.
5. Polygons with a large number of sides, two arch types can be obtained: semicircular and horseshoe, where the curve can be larger than a half circle. (Figure 23)

Parametric definition
Using the parametric-design software Grasshopper, this information can be synthesized in a single parametric definition. This allows one to vary the radius parameters, circumference subdivision, bar sections, hole diameters, and final dome configuration. (Figure 24) Describing the dome parametrically allows both design and, ultimately, the structure's manufacturing process to be optimized.

Polygonal Dome summary

The objective is to build a structure that is deployed simultaneously in both plan and elevation. It is proposed that the semi-arches rotate around the z axis with a rotation angle

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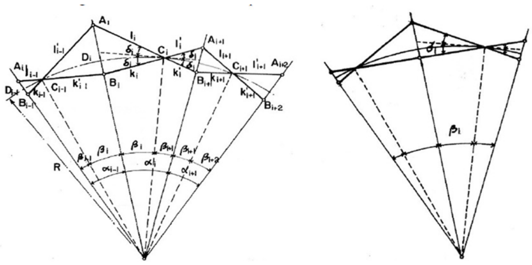

Figure 11.
The articulated points are projected radially.
Source: (Candela et al., 1993)

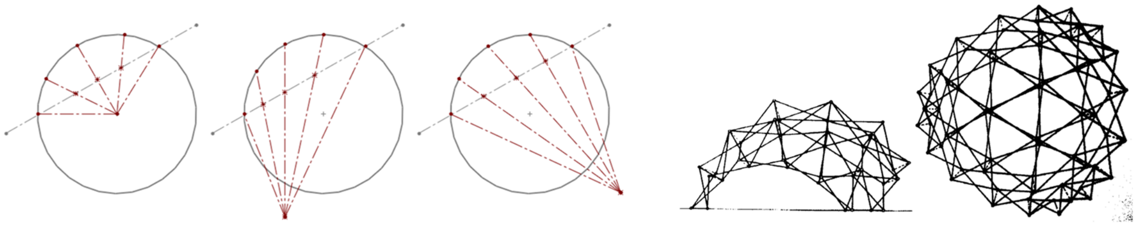

Figure 12.
Projecting points onto a sphere - different possibilities.
Source: (Escrig, 2012)

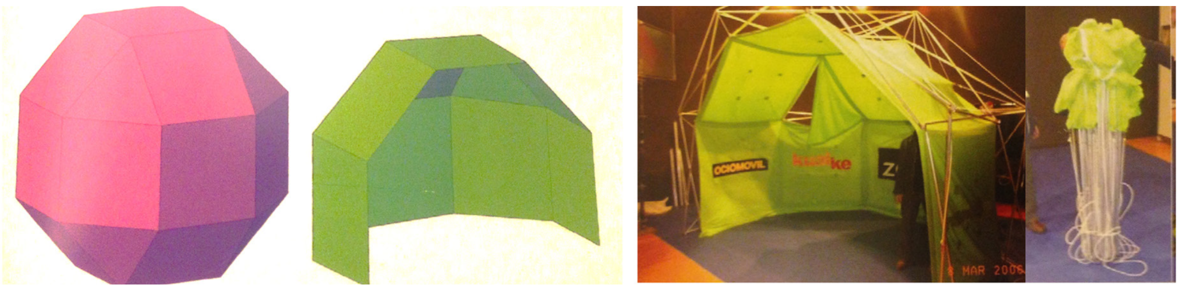

Figure 13.
Portable exhibition pavilion.
Source: (Escrig, 2012)

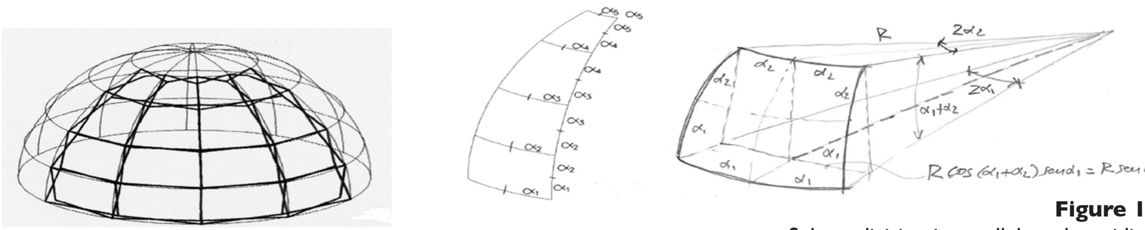

Figure 14.
Sphere division in parallels and meridians.
Source: (Escrig, 2012)

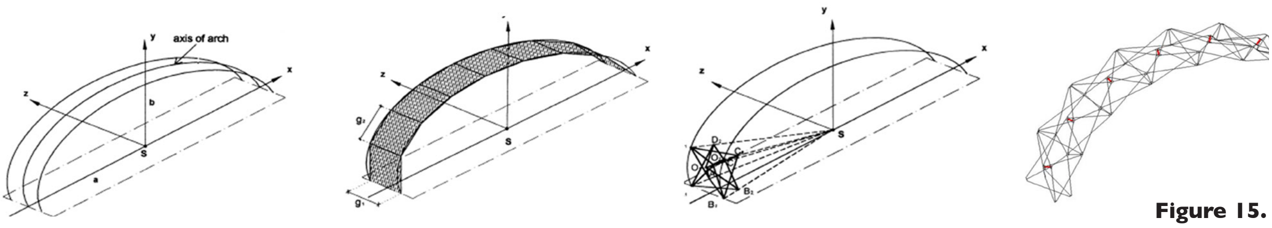

Figure 15.
Geometric design of complex-curved surface
Source: (Gantes, 2004)

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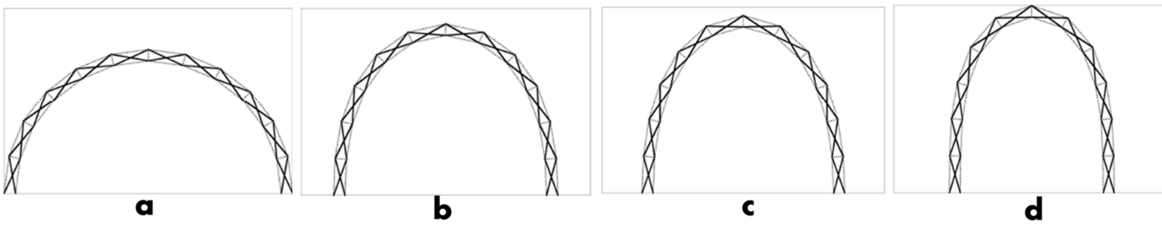


Figure 16.
a) Equally dividing. b) Arithmetic progression. c) Geometric progression. d) Algebraic equation.
Source: ((Babaei, 2009)

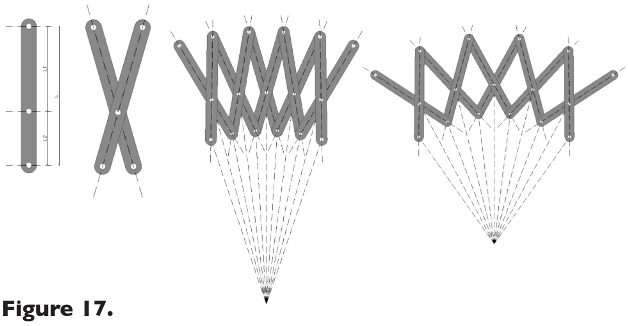
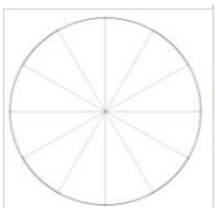
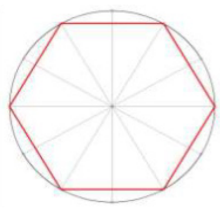
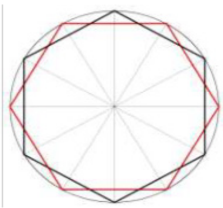
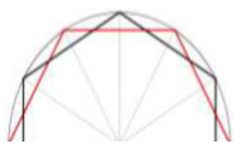


Figure 17.
Straight scissors with asymmetric articulation.









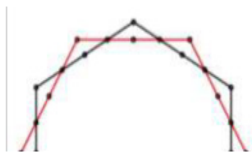


Figure 18.
Straight scissors with asymmetric articulation.

Figure 19.
First hexagon formed

Figure 20.
Two overlapping hexagons

Figure 21.
Deployable-arch projection

Figure 22.
Articulation points

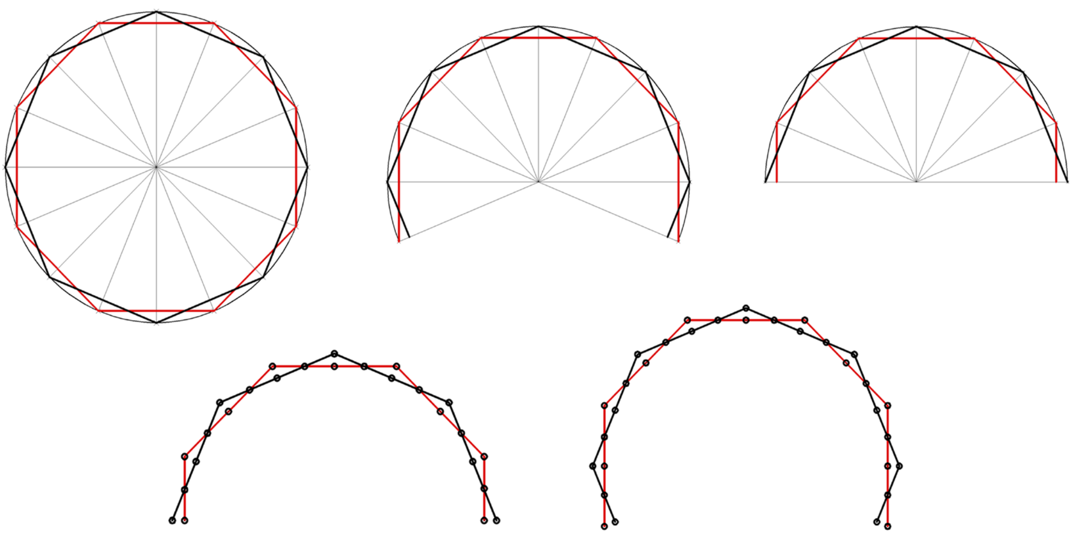


Figure 23.
Deployable-arch parametric definition.

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corresponding to the desired polygon shape. From this, scissor groups can be projected in horizontal plane, which directly relates to the vertically deployed arches. (Figure 25)
To allow the study of other geometric possibilities of regular polygons, the following method-summary table is provided. It distinguishes the following four key elements: polygon type, scissor group, bar length, positioning holes and axonometric domes with their height and possible outcomes. (Table 1, table 2)

Prototype construction

To bring the deployable arch implementation to life, a deployable (performance) stage and a deployable kiosk were designed for temporary-event use at the School of Architecture, Art and Design, at the Monterrey Institute of Technology and Higher Education in Mexico.

Prototype I. Deployable stage
Design
The prototype is a half dome with a regular heptagon geometric base the diameter of which was adjusted to the maximum height possible in the room where the stage was installed.
The arches were three meters high and horseshoe shaped. The plan has a circumference with a six-meter diameter, which includes the arch bases.
The prototype has five deployable arches, a folding-platform floor structure, and elastic-fabric covers between the arches (Torres, 2013).

Materials
Bars: cardboard tubes. Diameter: 5 cm. Thickness: 5 mm
Separators: bamboo. Diameter: 2 cm
Foldable platform: American pine beams and laminated-chipboard panels (recycled from old architectural drawing tables)
Cover: Lycra.
Top node: composite-aluminum sheet
Connecting hinges and screws: steel

Construction
The deployable arch is made from sixteen 1,36 meter-long cardboard tubes. For increased stability, a double layer of each arch was built. Varying-length bamboo spacers were placed between the double arches, which made the base of each arch wider at the bottom and narrower at the top.
The floor platform, which was not anchored to the ground, was formed from four symmetrical sections. The four panels are hinged, which allows each panel to be folded and unfolded. The panel support system were wood beams that were attached to the arch bases.
The top node or keystone was a sheet of composite aluminum designed to receive and anchor the upper arch ends. The design and installation of the keystone is still under study with the aim that, in the future, it would be incorporated into one of the arches.
A ladder was used to facilitate arch raising, maneuvering, receiving, and anchoring the arches.

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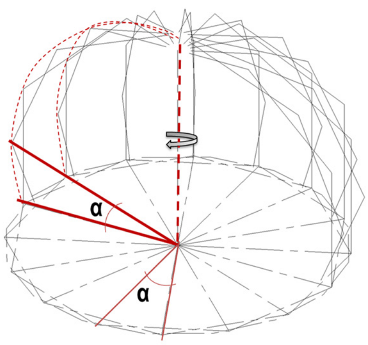

Figure 25.
Axonometric dome.

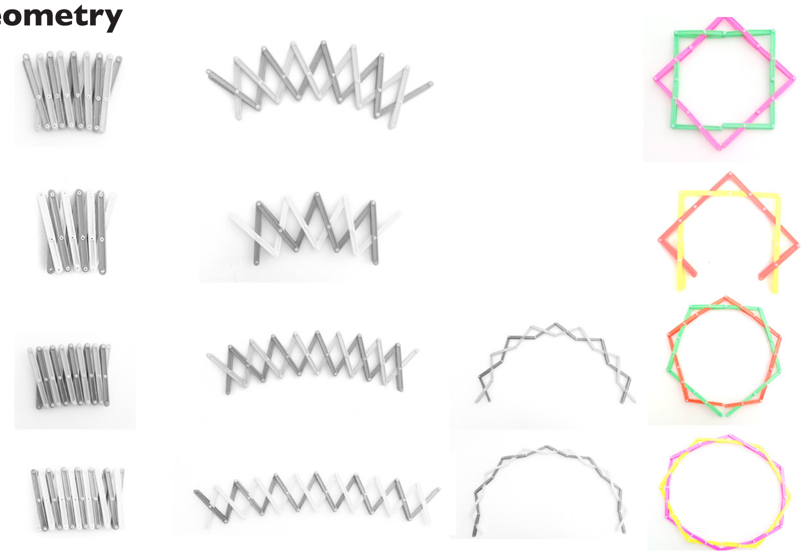

Figure 26.
Deployable polygons withstraight scissors.

SCHEME	VALUES	FORMULA	RESULT	Percent
c = (r) sinα α = 360°/2n n = Number of sides of the polygon b = (r) tanβ β = α/2 r = c /sinα	Radius (r) mts	d/2	3	
	Angle division circumference (α) degrees	360°/ 2n	45	
	Central articulation anglel (β) grados	α/2	22,5	
	BAR LENGTH BETWEEN AXES / POSITIONING HOLES (a, b, c/2, c)			
ESTABLISHED VALUES	Bar Length (c)	(r)sinα	2,12	100 %
	Middle length of the bar geometry (c/2)	c/2	1,06	50 %
Diámeter (d) mts: 6,00	Major segment of the bar (b)	(r)tanβ	1,24	58,58 %
Number of sides of the polygon (n): 4	Minor segment of the bar(a)	c - b	0,88	41,42 %

Table 1. Bar length and positioning holes

DIAMETRE CIRCUNFERENCE 6M		ARCH TYPE			BAR				DOME GEOMETRY		
6.00		< 180°	180°	>180°							
POLYGON	ARTICULATED BARS GEOMETRY	BASKET-HANDLE ARCH	SEMICIRCULAR ARCH	HORSESHOE ARCH	a	b	c	c/2	BASKET-HANDLE DOME	SEMICIRCULAR DOME	HORSESHOE DOME
					Meters (m)						
SQUARE	16 Bars		8 Bars	12 Bars	0,88	1,24	2,12	1,06	d= 6 h= 0,00	d= 6 h= 2,12	d= 6 h= 4,24
					Percent (%)						
					41,42	58,58	100	50			
					Meters (m)						
PENTAGON	20 Bars	8 Bars		12 Bars	0,79	0,97	1,76	0,88	d= 6 h= 1,50		d= 6 h= 3,35
					Percent (%)						
					44,72	55,28	100	50			
					Meters (m)						
HEXAGON	24 Bars	8 Bars	12 Bars	16 Bars	0,70	0,80	1,50	0,75	d= 6 h= 1,10	d= 6 h= 2,60	d= 6 h= 4,10
					Percent (%)						
					46,41	53,59	100	50			
					Meters (m)						
HEPTAGON	28 Bars	12 Bars		16 Bars	0,62	0,68	1,30	0,65	d= 6 h= 2,04		d= 6 h= 3,37
					Percent (%)						
					47,40	52,60	100	50			
					Meters (m)						
OCTAGON	32 Bars	12 Bars	16 Bars	20 Bars	0,55	0,60	1,15	0,57	d= 6 h= 1,62	d= 6 h= 2,77	d= 6 h= 3,92
					Percent (%)						
					48,02	51,98	100	50			

Table 2. Polygonal dome summary

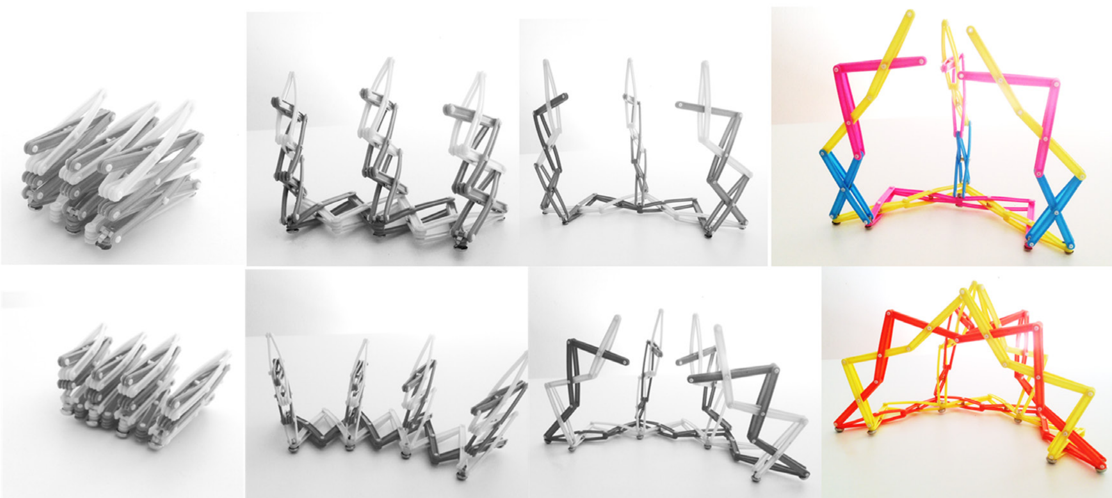

Figure 27.
Deployable domes.

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Assembly
The stage was made from of six components:
1.Beams.
2.Panels.
3.Base.
4.Arches.
5.Top node (keystone).
6.Membrane.
The components were assembled in the following order: Panels were place in the beams and the platform floor was unfolded. Once the bases were fixed, the arches were deployed. To finish, the top node was inserted and fastened, and the membranes were attached between the arches.

Deployment
The floor platform can be deployed manually by a single person due to the hinges between the beams. Each arch, which weighs approximately 15 kilograms, requires an individual person to deploy. Because the arches are lightweight, they are easily stabilized and it is easy to connect them to the top node. Approximate installation time: 40 minutes

Analysis via Software
The 2D graphics, made with WinEva software, show possible arch deformations depending on geometry. This analysis demonstrated that increased bar count and arch heights resulted in greater deformations.

Transport and Disassembly
Building the prototype allowed further development of a design that enabled easy assembly, disassembly, and transport including considerations of available transport vehicles. In this case, the complete floor platform was transported in a truck bed and it was not necessary to remove the panels. On the other hand, the foundation beams and arch bases were disassembled. The arches, bases, and membranes were transported as separate pieces. Approximate disassembly time: 15 minutes

Durability
The design and materials had a planned durability of a maximum of two weeks in an indoor environment. The stage was deployed for two different events. For the second deployment, it was necessary to reinforce the location where the bars met the top plate and the tubes developed cracks and deformation due to compression. These issues were due to self weight and anchor type. Unfortunately, several arches failed during the second disassembly.

Prototype II. Deployable KIOSK
Design
The prototype was designed as a half-dome deployable kiosk. The structure was 3.00 meters in diameter and 2.45 meters high. The main design goal was the ability to simultaneously extend both the arch (vertical) and floor (horizontal) scissors. The arches are designed to stop just short of vertical so that they can be fixed to the top plate but not so far as to cause the structure to roll over during deployment. This proposal did not include a platform, which made the structure lighter. The stage includes nine deployable

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arches, a base structure also formed by scissors, and elastic fabric between the arches.

Materials

Arch bars:	Rectangular aluminum bar = 1.00" x 0.50"
Separators:	Aluminum tubing = 0.325" x 0.05"
Fabric cover:	White Lycra
Keystone:	Aluminum-composite sheet
Connectors:	Steel

Construction

Arches: Each deployable arch was formed by 19 aluminum rectangular bars that were 0.72 meters in length. As in the first prototype, greater stability was obtained by using a double layer of deployable arches. The base structure was an arch defined by a scissor group, the base of which was a heptagon. This design optimized the opening (door) size with the maximum possible floor space. The top node or keystone had a new plastic design, which received the upper arch ends and was fastened with screws. In this case, the design progressed by using digital printing, but, it should be noted the first attempt did not fit and needed to be redesigned. (Fig 39) To assist in attaching the top node to the arches, a ladder was used.

<u>Assembly</u>

The kiosk was made up of five parts:

1.Nine vertical deployable arches.
2.Connection nodes.
3.Top centre piece (keystone).
4.Horizontal deployable arch.
5.Fabric membrane.

The nodes allow the horizontal arch to be connected to the nine vertical arches. Once the structure is deployed, the top centre piece is inserted and connected to the arches then the membranes are fixed between arches.

<u>Deployment</u>

The slenderness and quantity of vertical arches complicated the deployment and required a minimum of five people to stabilize the structure. Once the top center node was inserted and connected, the structure became stable and fairly rigid. Similar to traditional arch construction where stability occurs once the keystone is set, the structure became stable when the center node was connected.

The structure was raised into place by four people while a fifth fastened the center node and arches.

Approximate weight: 40 Kg.

Approximate assembly time: 20 minutes

<u>Transport and Disassembly</u>

The structure was separated into two parts, which allowed it to fit into the trunk of a small car. Compared to assembly, disassembly was much quicker. Once the top node was disconnected, the structure was easily collapsed.

Approximate disassembly time: 10 minutes

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Figure 28.
Deployable stage made from cardboard tubing.

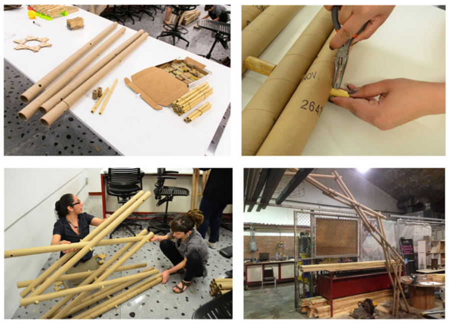

Figure 29.
Arch assembly.

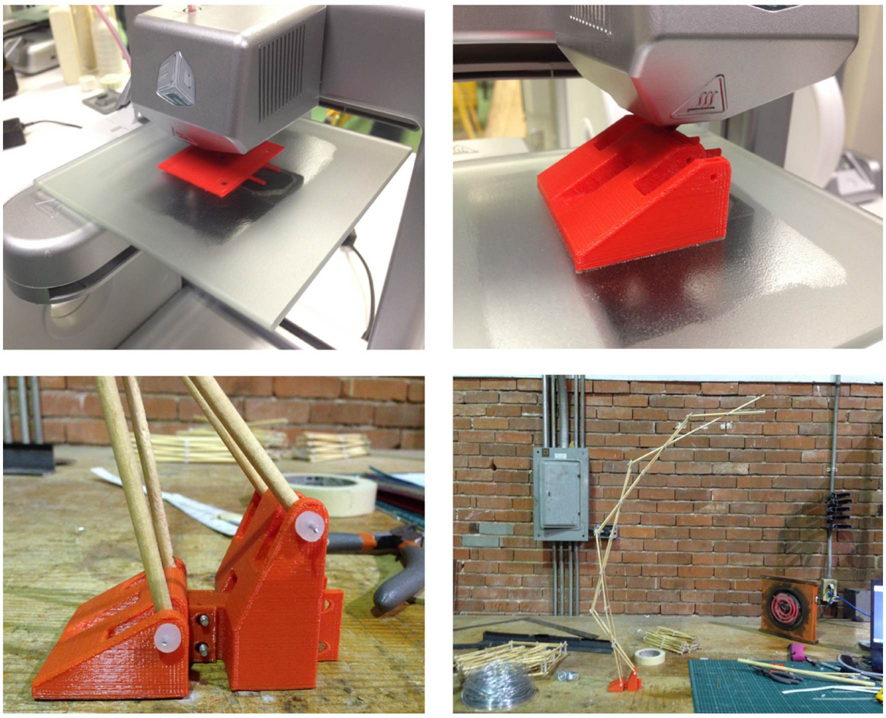

Figure 30.
Base manufactured using a 3D printer. Scale model: arch base.

Figure 31.
Base box construction.

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Deployable Arches Based on Regular Polygon Geometry

Figure 32.
Floor-platform assembly.

Figure 34
Deployment process.

Figure 33.
Fasteners and connection detail.

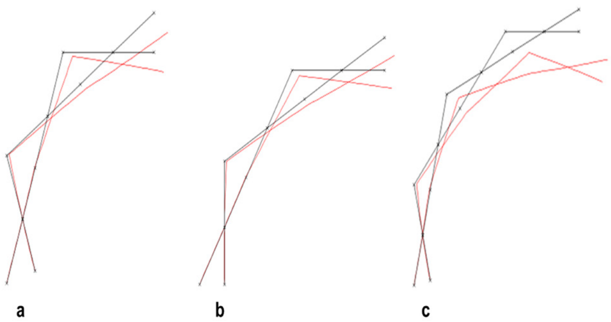

Figure 35.
Arch deformation. a) Pentagon. b) Hexagon. c) Heptagon

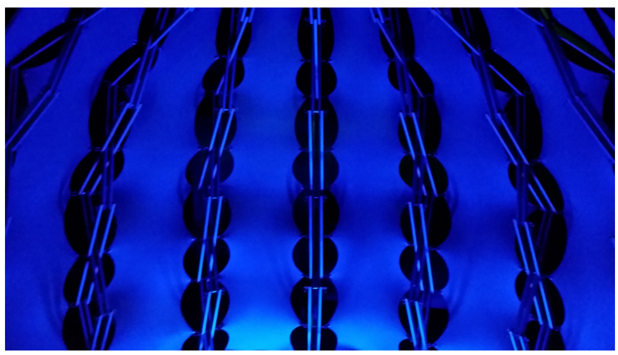

Figure 36.
Front view - Deployable kiosk.

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Durability
The deployable kiosk was designed to last five years. As of this writing, the structure has been successfully used for three different events for a minimum of five days per event and remains in excellent condition. Current investigation focuses on improved deployment and covering and the optimal top-node design.

Conclusions

After the geometric analysis and the construction of the prototypes, the following can be concluded:

-The proposed method allows for the design of arches and an assembly system, which is based on traditional arch construction. This is done through the use of two principal concepts: (1) regular polygon geometry and (2) deployable structures with articulated bars that are also called scissor systems. Using this methodology, it is possible to optimize the design and assembly of deployable domes.

-The regular polygon geometry determines the: Arch curvature; Bar quantity and length; Bar mounting-hole location (hinge point); Arch opening limit to achieve the proposed curvature; Arch final deployable state.

- Arches based on polygon geometries. The network of lines that is generated serve as a guide to join scissor groups with eccentric articulations, which allows different types of geometries to be visualized. (Semicircular or horseshoe arches)

- The deployable-structure scissor-hinge system allows the arch to be assembled by means of two parts joining together at the peak (matching traditional arch construction). This proposal, as a deployment structure, avoids the need for any external structure or supports during assembly thus simplifying and speeding up the process.

-The proposed scissor system is easy to manufacture, assemble, and install as the modular elements optimize construction.

-The geometry form-finding process utilized in this research allowed for the development of a parametric definition, which established the fundamental geometry basics. It was able to be used to define parameter variables such as:
The circumference diameter and the number of segments it can be divided into; bar length, thickness, and geometry; and the hole diameter for the connections between bars. This allows for dome geometries to be calculated and adjusted very quickly, which enables design flexibility.

- Each of the parametric designs has generated valuable solutions to the geometric concept, which results in more efficient design, manufacturing, and assembly. In addition, a new way to design deployable structures through variable geometric parameters was developed, allowing several domes for different architectural requirements to be designed.

- Building and assembling the prototypes allowed the deployment process, the impact of bar material on performance and durability, and transport and assembly challenges to all be observed.

Future research will investigate the maximum opening point of the arches, taking into account the top node weight and structure deformation, to obtain the exact geometry.
The methodology presented here is a geometric process that has been tested with prototypes, structural studies, and load analysis. This research is still in process, with the aim to optimize the deployment time and resolve the top node geometry.

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Figure 37.
Deployable Stand.

Figure 38.
Assembly process.

Figure 39.
Connections and details.

Figure 40.
Deployment process.

Figure 41.
Structural testing.

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Prototyping Structures in Architecture

Guest Editor: Marios C. Phocas

Associate Professor, Department of Architecture, University of Cyprus

The 9th issue of the **archiDOCT** e-journal welcomes papers that explore the design, analysis and development of prototype structures in architecture per se, as well as the processes followed in the creation of innovative structural solutions within contemporary architecture. Prototype structures may address aesthetic, form, material, system, fabrication or even energy efficiency related aspects in achieving innovation and advancement in contemporary architecture. Related developments are most prevalent since initiation and application of numerical methods of analysis that revolutionized architectural technology and engineering in the early 70s, and distinguished throughout design and computational analysis, design optimization and automated manufacture and open-loop multivariable system performance-based design. While computational analysis initially led to a discretization of the disciplines involved, in the processes of form creation, primarily derived from abstract aesthetic and functional reasoning on the one hand, and numerical calculation and optimization on the other, advances of digital design technology enabled through linear, sequential developments of form, design and construction, single or multi-objective optimization processes to be achieved following any intermediate design results. At the same time, digital technology opened many possibilities for integration and shift from mass-production to mass-customization in an effort to relate the principles of the former with the advantages of bespoke fabrication. Meanwhile, computational platforms of operation and real-time performance simulators enable iterations of system simulation, numerical verification and optimization, and may even shift the focus of design towards bottom-up processes primarily influenced by aspects of structural geometry, morphology, material and performance. Thus, open loop developments in multivariable, transformative systems may be achieved from early conceptual designs to fabrication through respective research-based design processes.

This **archiDOCT** issue invites publications on doctoral research in progress focusing upon aspects of design, simulation, analysis, experimentation and fabrication of individual prototype structures, as well as integrated interdisciplinary modes of operation in generating new, innovative and transformative structure design solutions in architecture.

Important dates

Submission deadline (full papers): 31 March 2017

Review period: 31 March 2017 - 31 April 2017

Revision period: 31 April 2017 - 31 May 2017

Publication date: 01 July 2017

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