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The Big Roof. for a Theory of Design through the Permutation of the Big Formal and Structural Types

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ABSTRACT

The topic of the large centrally planned hall is one of the oldest ones in Building History; with different techniques and since Pre-Christian times, builders have always aimed at imagining and realizing a centrally-planned space surmounted by a big roof. Such ambition has never disappeared and today the projects focusing on this topic are innumerable also thanks to the advancements in the construction techniques and to better materials.

Do all of these buildings, both the recent and the less recent ones, share features and rules that make them belong to a same family of structural forms?

The work we carried out is not meant only to prove that the "genealogical lines" that unite different planning experiences do exist, it aims for something more. Indeed we suppose and then prove that entire families of architectures are referable to formal and structural geometry rules from which we can abstract planning codes that allow modern planners to operate through the permutation of such original types.

KEYWORDS: Architectural Design, Big Roof, Structural Types, Parametric Application; Innovative Design and Construction Methods

1 THE TECTONIC RELATIONS BETWEEN ARCHITECTURAL DESIGN AND STRUCTURAL MODELING

The analysis of Big Roofs allows dealing directly with linguistic and methodological issues underlie the relationship between Design and Construction, definition of the architectural Form and Calculations of constructions.

Research on the construction for setting architectural form has always been the basis of the theory of architecture, starting from Vitruvius and his reflections on "assemblage of solids", passing by Leon

Battista Alberti and his attention to the order of arrangement of the materials, to the definition of "resistant part" in the Middle Ages. Modern research on the bearing structure and its important consequences on the architectural language start with the identification of the tectonic "joint" in the nineteenth century (by Bötticher to Essenwein).

The architectural design is confronted initially with the construction through the "pure geometric forms" and the intuition on static (until the sixteenth century). Subsequently, the design rules and construction of architectural proportion began to deal with the analytical language of differential calculus and mathematical-mechanical models (from the seventeenth to the eighteenth century.). This transition initiated a separation between the design architectural form and design of the structure.

The combination of mechanics and mathematics, which took place in the first half of the nineteenth century (Claude-Louis Navier was one of the protagonists), led to the rationalization of the design process and allowed the definition of the Science of the "art of building". So it began the division of architecture and mechanics of construction.

The world of architectural design ended up separated from the world of construction also due to the adoption of Complex Shapes during the early '900. These shapes were derived from theoretical mechanics and computational machine. The structural analysis, therefore, reverses the terms of the design, determining the form from the state of stress.

In fact, the Italian engineer Pier Luigi Nervi (1891-1979), stated:

"*The continuous increase in size, the complicated function of buildings, the improve of construction methods and of the strength of materials, the increasing acuteness of the analytical procedures and experimental static verification, put out every day the importance of engineering problems and their progressive development fit in the architecture itself*" (Nervi, 1959).

Nervi immediately understood the risks of this comparison of the shape of the design process with the analytical procedures. Indeed, Nervi wrote: "*The application of theoretical research (based on math) to the study of the internal balance of resistant systems, which began in the last century and gradually expanded to the current development, has brought a formidable aid to solution of static problems, but has inevitably contributed to dry up the sources of intuition and sensitivity of static. This has encouraged the separation between technical-mathematical mentality and artistic-intuitive one, clear in the educational and professional division between engineers and architects. This division is one of the causes of the crisis in which it is the architecture for several decades now"* (Nervi, 1945).

1.1 The role of the model in the architectural design and construction, between past and future

The latest digital tools allow merging again the design of the form with the definition of the structure. Today it is once again possible merger of the geometric model with the mathematical and mechanical model during the design process of the form, revealing the overcoming of the crisis identified by Nervi.

It is precisely the model the underlying theme of this relationship between design and construction. Leon Battista Alberti often describes the importance of the model. In fact, he wrote: "*Therefore I always highly commend the ancient custom of Builders, who not only in Draughts and Paintings, but a real Models of Wood or other Substance, Examined and weighed, over and over again, the whole of Work and the measurements All its Parts, before they put Themselves to the Trouble or Expense. By making Model you will have an opportunity, to thoroughly weigh and Consider the Form and Situation of your Platform with respect to the Region, what Extent is to be allowed to it, the number and order of the Parts, the Walls are how to be made, and how strong and firm the Covering*" (De re Aedificatoria, Book II, chap. I).

The model has always had an instrumental role not only in the design but also the training of designers in fact, still Alberti wrote that thanks to the models could know the rules of construction and start testing.

From the beginning, the structural mechanics and Science of Constructions used the instrument of the "modeling" to "build" their physical-mathematical models that describe the static and dynamic behavior of the structure resistant of architecture and its structural elements. Among the models there are structural frames, rope and truss beams, membranes, plates, shells and space frames.

The model has always been a tool of project and control, we think of Gaudi and his “reverse” model; Heinz Isler and inversion of hanging membrane models; Frei Otto and his experiments with the models of uniform tension and minimal surfaces; Musmeci and its innovative models with elastic membranes.

These experimental models translated into “built form” the results of research on mathematical models that instead concerned only the "modeling" of structures. So the material models represented an attempt to mend the gap between the determination of the structure and design of the form, before moving to the construction site.

Today, the concept of “modeling” is still paramount and is the basis of digital design, which allows us to make three-dimensional models were born directly from the mathematical models. There is in fact a fusion of techniques of computer modeling and generic algorithms: techniques morphogenesis and structural modeling techniques. It can therefore be noted that today the digital modeling able to make their own simultaneous design of the form and the translation of the structure.

Fact today the designer can speak of “Resistant masses” and “Resistant forms” through structural models: Linear (beam-plate, rod-plate) and curvilinear (cable-membrane, rod-shell). The link between choice of structure and formal language is more direct. Any structural system finds its spillover effects in the design of the form.

The engineer Sergio Musmeci (1926-1981) had anticipated this reversal of the relationship between architectural form and structural tensions, materialized today from digital design. Musmeci had held that the structural design of the real unknown is the form, not the tensions, which are calculated from the identification of the form.

Just the design of Big Roofs has enabled us to define the morphological relations in the different structural models, especially membranes, discrete systems of geodesic and reticular structures, and continuous systems of thin-shells and tensile structures.

Many relationships between structural systems (Bending resistant, Axial resistant, Form resistant and Tensile resistant) and construction techniques are yet to experience, and language outcomes have still not been “keyed”. Maybe this will be the task of the new designers who have found, during their training, the combination of design and construction of architectural language. Even the architect must recover the static sensitivity and intuition to manage the discovery phase of the form (morphogenesis) in a design process, checking simultaneously the architectural formal approach and structural engineering.

2 THE DESIGN AS PERMUTATION

Is the design a new interpretation of an antecedent idea? Is the design the innovation of an already known idea? On the other side the design has to be a pure invention in its relation with the past; so we can define something new as a real design if it is actually atypical, innovative, unexpected, disorienting. This path leads to a minefield where stands of position prevail and where the contact with the actual “designing process” is missing. It’s important to remember that design is a physical based art, and this means that the building follows the design; only words about it don’t represent art.

The direct link between architecture design and antecedent form is undeniable: the use of a specific material, a particular aspect of design or the whole generative idea can put in evidence the relation whit preceding works. This possibility results from the designer’s capability of restarting or resuming an architectonic problem from any point in historical contest.

In Max Berg’s Jahrhunderthalle in Frankfurt is evident the intention of referring to the great domed and gemmate forms that made notorious roman, byzantine and then ottoman building art; it symbolizes a clear formal citation without that masonry’s continuum that characterized deeply that tradition.

Viollet-le-Duc's reasoning about his "Entretiens sur l'architecture" generates a gentle equilibrium in the Future Pavillion in Siviglia (1992); what is clear here is the idea about the material's role in structure according to their resistance and not a formal contiguity or a stylistic citation.

The Architectural design results inevitably from historical background, and most of all from techniques that rule an historical age; scientific researches, technical innovations, materials and tools evolution change cultural prospective and then influence also styles and formal sensibility. All works from great architects and engineers like Pierluigi Nervi, Eduardo Torroja, Robert Maillart wouldn't have been possible without a "new" material like reinforced concrete. Even the acceleration of the modern architecture since the great steel structures of the XIX.th century results from the scientific capability of controlling behaviors models, capability that started with great Post-Renaissance scientist like Galileo Galilei. So it could be argued that the characteristic of fluency omnipresent in our age's architecture is possible thanks to design tools of the digital revolution.

Therefore, designing is like a permutation, a mutation of an ancient idea that depends on cultural and technical conditions of the period, a mutation by a mind that synthesizes, plans and realizes. The big roof topic is probably the architectural type that mostly explicit the reasoning realized until now. The necessity to cover a big span with a unique designing act resumes naturally the architectures that dealt with it in the past and puts in evidence the technique's innovation role in design choices. Therefore, a permutation isn't only a formal variant of a past architecture or only a constructive evolution of a form.

A permutation is a new synthesis between the intelligible dimensions of the project that relate to the "indelible issues" of research design that have always been there through the technical and cultural spirit of an era. A project like permutation can start from any formal idea and technique and evolve even in complete contradiction to the starting conditions. Permutation does not mean copy, or something change slightly; permutation means to start from a theme to translate a new project even with the reversal of some of the settings, or even with the renege some of the assumptions.

We could start from the Beijing National Stadium designed by Herzog & de Meuron to understand the idea of the project as a permutation The dominant idea is the possibility that a "natural" structural shape can be an inspiration for architecture; the nest allows a form as a "Cup" through a tangle of twisted branches which is claimed not thanks to a structural hierarchy between the elements but for the mutual aid between the parts where none is primary or secondary.

In this case, the structural idea determines the formal aesthetics on which the architects work to design a stadium, well beyond the size of a nest. Galileo taught that the scale factor of the structures does not cause a direct proportionality to dimensional increase. So the translation of the executive project adopts a structural hierarchy completely detached from the original idea with the aim of maintaining a close formal relationship between the scale of the project and the thickness of the "branches". The frame is constructed by truss beams then connected together to reconstitute the idea of the nest, with the aggravating circumstance of casual form of the "plots" that makes all sectors different for the industrial production.

The example of the permutation that we have experienced (Figure. 1-2) adopts the idea aesthetics and structural strategy, but we fundamentally change the geometry generation, here we abandon the "formal randomness of the plot" in order to model starting from a serially polar geometry, which on the one hand optimizes the structural behavior, as always in cases of central plan, and on the other systematize the production of the parts by configuring a constant series of elements.

The Philips Pavilion for the Universal Exhibition in Brussels in 1958 is another example that we have analyzed. This is a project that starts from hyperbolic paraboloid which is geometric shape and form very complex, but highly regarded by the world of construction. Le Corbusier designed the Pavilion by combining a series of portions of paraboloid with different matrices, forming a figure without a clear layout. This leads Yannis Xenakis, the "analytical" executor of the project, to use self-supporting individual parts despite the formal unity.

Our permutation (Figure. 3-4), even in this case works on properties "immortal" of space at the central vocation; we use one parabolic module that is repeated three times with the structural idea that each of them is reciprocally supported by the other.

Also the design research of Felix Candela is based on the figure of the hyperbolic paraboloid. He uses the quadric to design a polar architecture set on different polygonal shapes and covered by thin membranes “form resistant”. The thinness of the membranes should lead structures to work only in compression schemes to avoid flexural. This time the permutation reverses the structural behavior and plans a tensile structure on the same ribbed shape (Figure 5).

Figure 1: Sports Hall. Permutation design. Giannico V., Gianluca C. Architectural Design Studio 3°. Prof. C. D’Amato Guerrieri, Prof. N. Parisi, D. De Mattia

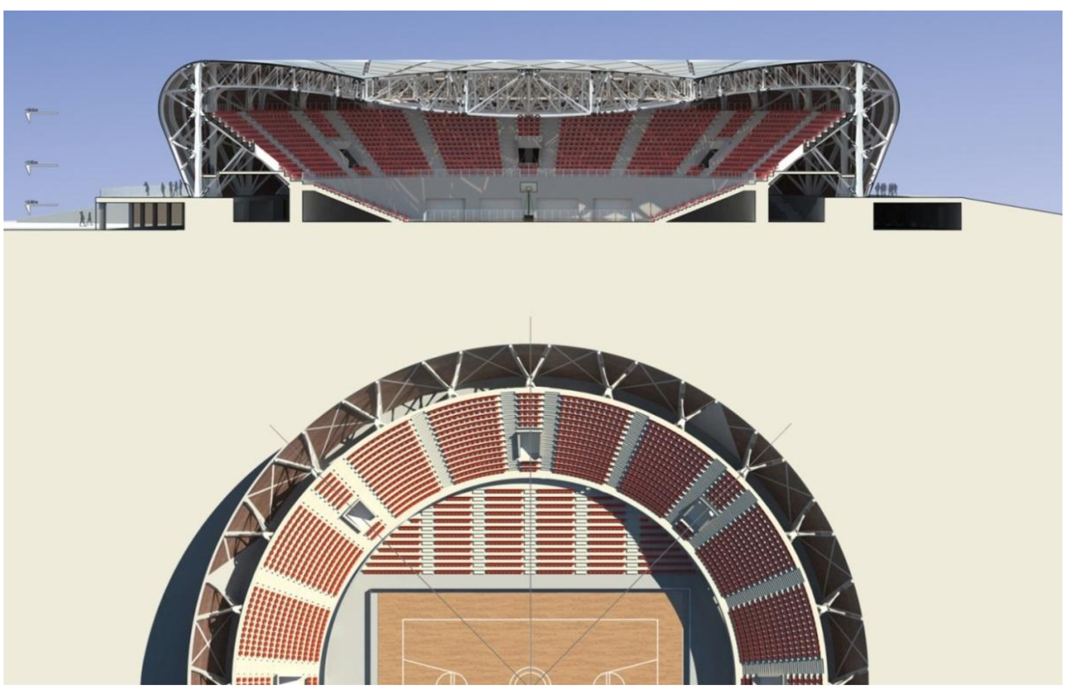

Figure2 : Sports Hall. Permutation design. Giannico V., Gianluca C., Architectural Design Studio 3°. Prof. C. D’Amato Guerrieri, Prof. N. Parisi, D. De Mattia

Figure 3: Aquarium. Permutation design. Chiancone C., Berardi G., Architectural Design Studio 3°. Prof. C. D’Amato Guerrieri, Prof. N. Parisi, D. De Mattia

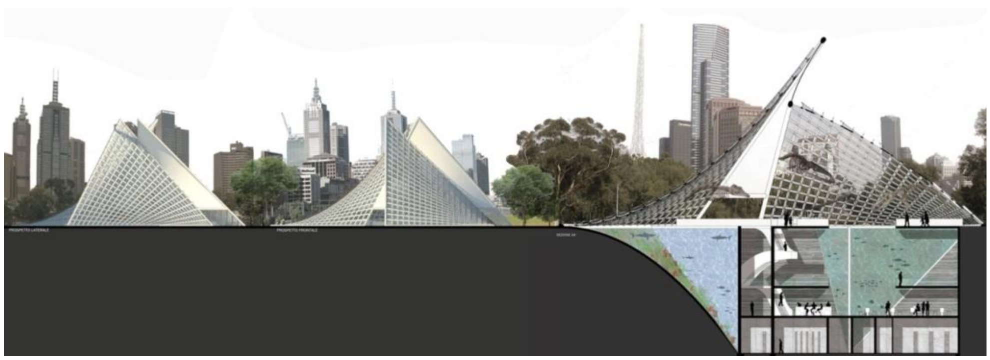

Figure4 : Aquarium. Permutation design. Chiancone C., Berardi G., Architectural Design Studio 3°. Prof. C. D’Amato Guerrieri, Prof. N. Parisi, D. De Mattia

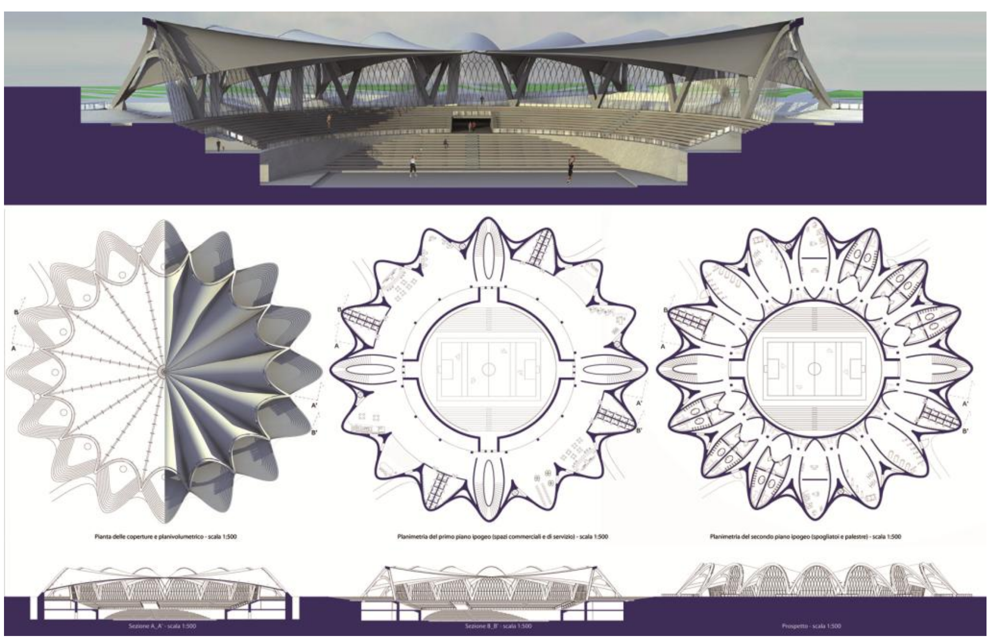

Figure 5: Sports Hall. Permutation design. Mastandrea F., Guzzoni Iudice A., Architectural Design Studio 3°. Prof. C. D’Amato Guerrieri, Prof. N. Parisi, D. De Mattia

3 STRUCTURAL OPTIMIZATION OF THE FORM

There is often a particular relation between architecture and structural engineering in modern constructions: each part is often considered separated from the other and the design runs on different railways; so happens that the architect "designs" and the engineer "calculates". This type of approach is admitted in ordinary constructions (reinforced concrete frames, ordinary masonry) in order to reduce design costs, but is also applied in non-ordinary ones where "aesthetic reason" should be stricter: this is allowed for the lack of specific figures that can manage modern tools to reach this aim.

We can count two types of losses in the last case: aesthetic losses, but even economic losses. Economic losses result from a "not-wise" structural optimization that could lead to a reduced amount of construction materials, while design costs remain the same.

There are eminent examples of structural optimization even without modern tool supported by PC, like Musmeci or Frei Otto. Today we don't need necessary to use soap films or ropes to try to model in different scale something we want to optimize because modern computational tools help us. A very powerful tool is Grasshopper, the parametric modeller based on Rhinoceros. Is possible to use Grasshopper as a Rhinoceros's plug in, but it isn't a totally graphic interface like Rhinoceros and works in different ways.

In this appendix, the hyperbolic paraboloid used in much architecture (Felix Candela, Le Corbusier) is analysed using Grasshopper. The aim is an algorithm that let to control the whole geometric aspect of the figure, and that let to optimize the thickness depending on the load condition (position, entity, etc.).

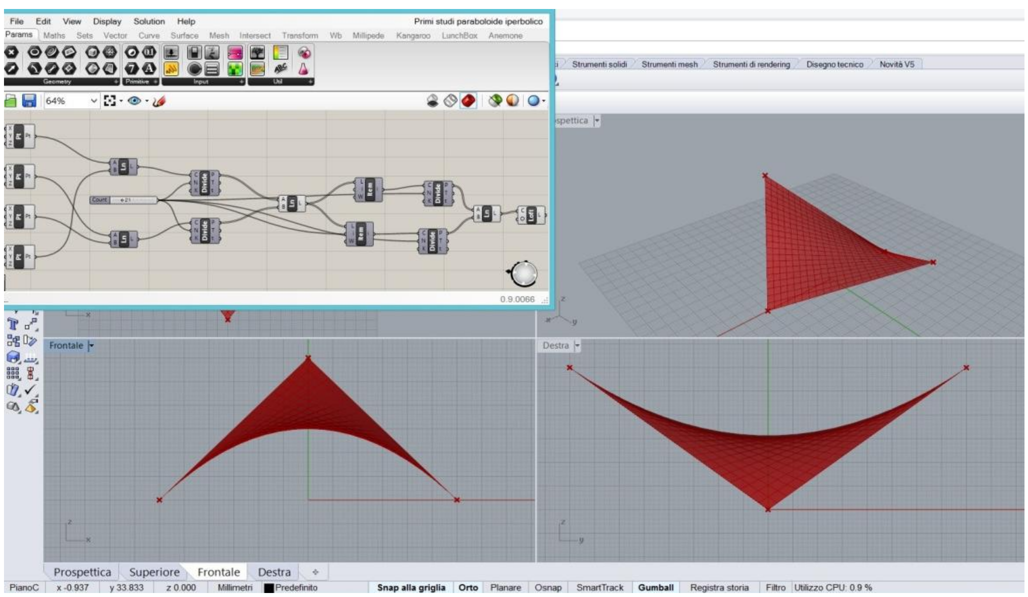

Figure 6: Hyperbolic paraboloid with Grasshopper (model by F. Parisi)

The paraboloid can be built on different geometric figures, all with even number of sides.

It's important to link all the components of the algorithm to each other's in order to exploit the power of parametric modelling. In this case it has been necessary to link the elements that form the base geometric figure (number of sides, vertexes, etc.) with to some elements that will generate the three-dimensional hyperboloid itself.

It has been necessary to use a particular Grasshopper plug-in called "*Anemone*" that let to design loops and iterations of the algorithm; all this because loops aren't properly in Grasshopper's "*modus operandi*".

At the end of this first part of the algorithm, the hyperboloid is parameterized by a certain number of elements important to control it directly.

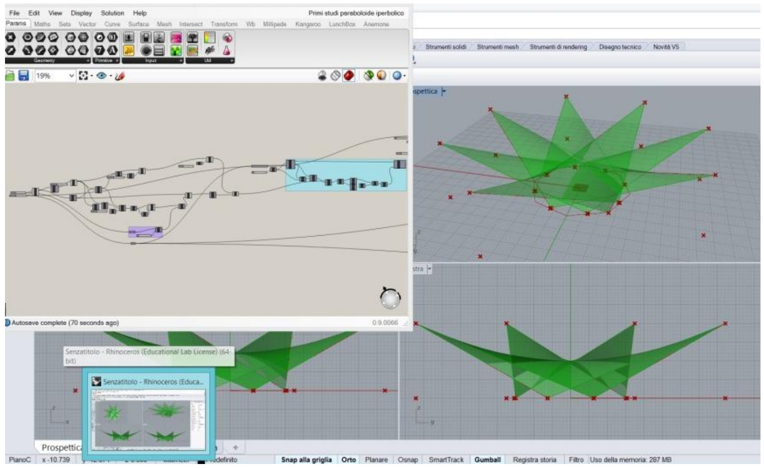

Figure 7: First step of hyperbolic paraboloid construction based on octagon (model by F. Parisi)

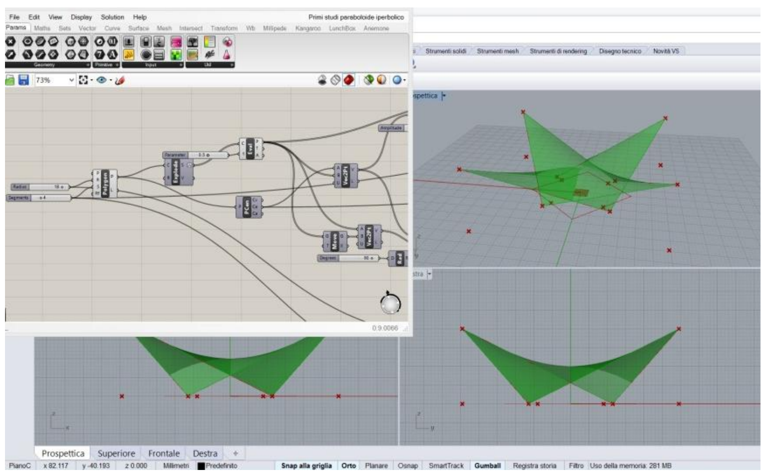

Figure 8: First step of hyperbolic paraboloid construction based on square (model by F. Parisi)

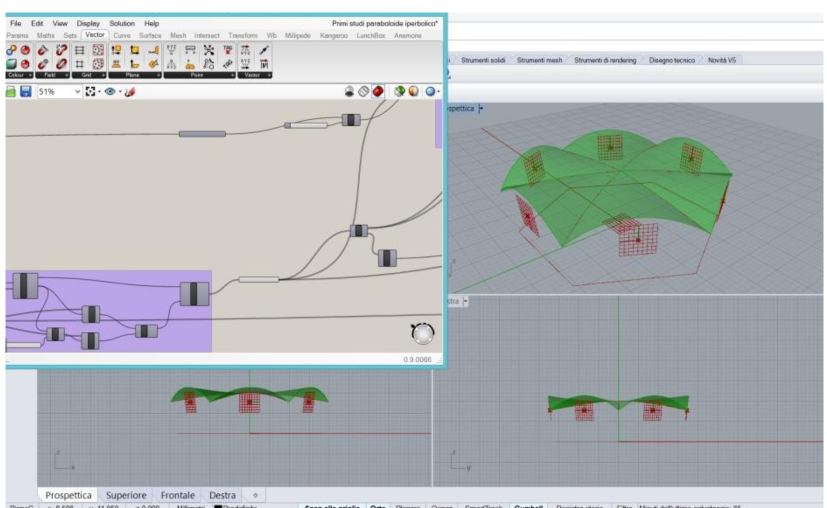

Figure 9: Completed hyperbolic paraboloid on hexagon (model by F. Parisi)

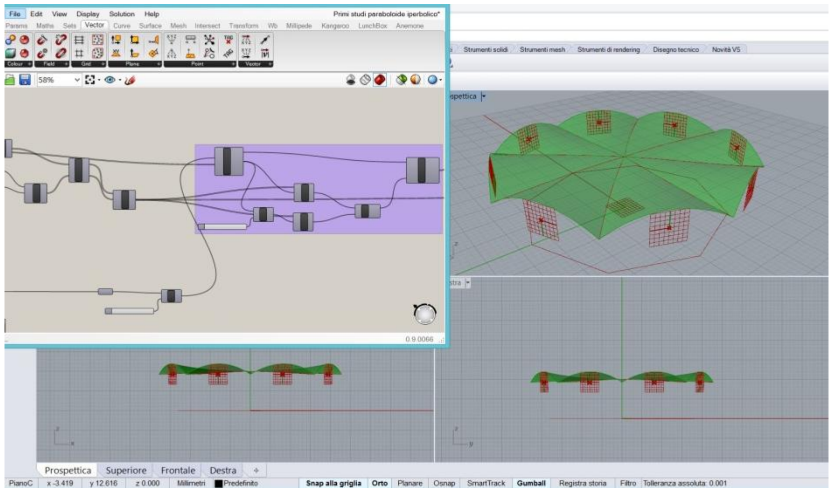

Figure 10: Completed hyperbolic paraboloid on octagon (model by F. Parisi)

In the second part of the algorithm it is necessary to use other plug-in: the first can turn our geometry into a finite elements system that let structural analysis (*millipede*), and the other is a solver that can perform maximization and minimization (*Galapagos*). By turning the hyperboloid surface into a mesh surface, it's possible to control the parameter we want to influence the form of paraboloid (mesh thickness, best curvature for the roof, etc.) and to link it to the solver Galapagos, according to load and boundary condition. This research will display the better solution for our aim (minimum Von Mises stress, no bending moment, etc.).

Concluding, *Millipede* is a free plug-in like *Grasshopper*, *Anemone* and *Galapagos*, but it performs only linear analysis. This is an important aspect because architects and engineer must consider even second order effects in this type of structure; but this isn't a problem because Grasshopper let to generate mesh into a Rhinoceros file that can be imported in specific structural software to consider second order effect in an optimized form, and not in a generic one.

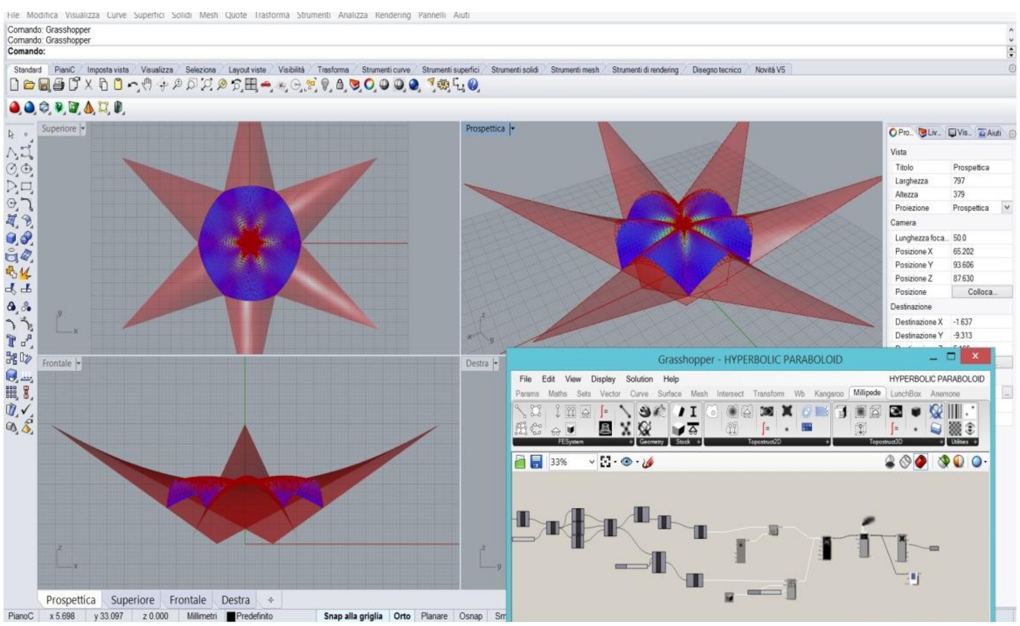

Figure 21: FEM analysis (model by F. Parisi)

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