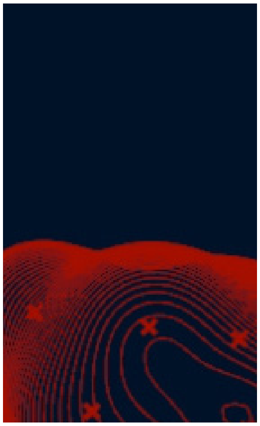
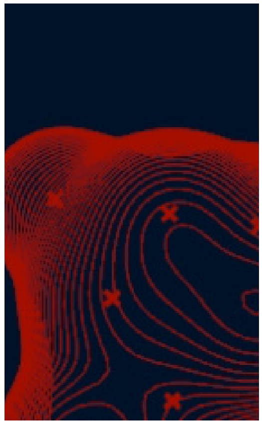
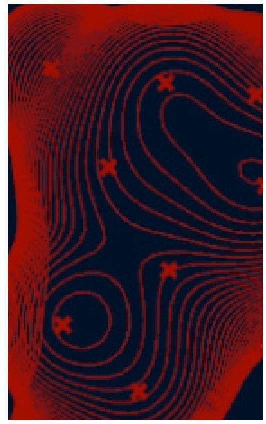
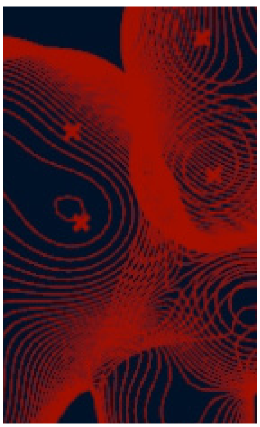
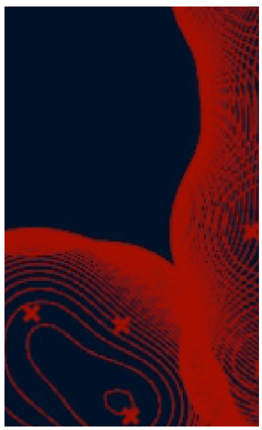
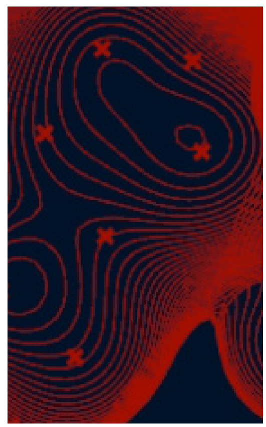
Geometrical morphogenesis in Architecture assessed through digital environments & the scope of performance based design tools.

Politecnico Di Milano

Scuola Di Archittettura e Societa
MSc In Architecture

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Abstract

The thesis aims to critically investigate the role of digital tools in architectural field, evaluating geometrical concepts in order to understand inherent processes involved in most of contemporary projects. Furthermore, as morphological exploration is embracing the architectural discourse, the thesis evaluates how appropriate are these digital geometrical concepts when are analyzed under a performance aspect. Assessing its morphological convenience related to climatological aspects as wind and solar simulation analysis.

Introduction

Digital technologies are transforming the architecture practice in several ways we couldn't anticipate before. Most of these technologies are characterize by being digitally driven processes, inherently dynamic, open-ended and unpredictable. What's more, the employment of digital technologies and the manufacturing advances already seen in the automotive, shipbuilding and aerospace industry are allowing a new dimension in architectural design. The continuous advances in computer aided design (CAD) and computer aided manufacturing (CAM) are encouraging the production and construction of very complex forms that were either impossible or too expensive to design using traditional technologies. Digital Revolution is helping to the rise of new digital architectures; these rely on the expression of curvilinear and highly complex forms. As peter Zellner declares in Hybrid Space: " Architecture is recasting itself, becoming in part an experimental investigation of topological geometries, partly a computational orchestration of robotic material production and partly a generative, kinematic sculpting of space." Contemporary architecture design approaches, are highly influenced by digital technologies, as well as some of the writings of prominent philosophers of the 20th century. One outstanding figure was Gilles Deleuze, French Philosopher. In his book "Thousand Plateaus"; he exposes a multiplicity of positions from which temporal constructions can be shaped, avoiding the linearity and succession; meaning that events are not organized in a continuous thread. Several contemporary avant-garde architects adopted these positions, in order to confront the omnipresent linear causality of design thinking. On 1993, Greg Lynn published his essay called " Architectural Curvilinearity " in which he exposes the different approaches into design, converging mainly in the idea that he calls "fluid logic of connectivity". His idea of this new fluidity of connectivity is manifested in a design strategy called "folding" which departs from Euclidean geometry of detached volumes that are manipulated by a topological conception of form, seeking as its ultimate expression a geometry that is described by continuous curves and surfaces. As Folding, Deleuze introduced new terms and concepts in his work such as; multiplicity, affiliation, smooth, pliancy and striated space in his book "the Fold". Deleuze goal relied in describing baroque aesthetic and thought, presenting fold as an uncertain spatial concept, as a figure and non figure, an order and not order, which was understood by formal thought; as the creation of smooth surfaces and transitional spaces between the exterior and interior, between the building and its surrounding. Some architects based their experimentation on the states of non Euclidean geometries; others based their studies on the spatial investigations of topology.

As mentioned before, digital media in architecture shifted from being a representation tool to act as a generative tool for the origin of form. Designers focused more in creating an internal generative logic, which led to a range of formal possibilities from which the designer would choose the most appropriate for further development. Additionally, the possible design models properties allow them to be consistent, continual and transformative, leading to replace the static norms and conventions architects had in their processes. The generative processes are convening to open a gate into new explorations in formal, tectonic and conceptual studies, architecture morphology is recasting in emergent properties of form. Therefore, the paradigm evolves from "making of form" to the "finding of form" due to the qualities of the digital driven techniques.

Non – Euclidean Geometries

During centuries architectural discerning was operating under the scope of Euclidean considerations and platonic solids; sphere, pyramid, cylinder, cube and prism were considered the essence of the Egyptian, Roman and Greek architecture as exposed by Le Corbusier in his book Vers une architecture, later on, they became the geometrical primitives of the digital modeling software and the notion was no longer about isolated archetypes, but more about quadric parametric surfaces. Euclids five postulates about geometry were particularly self evident excluding the fifth one that stated "parallelism". This last one led to the study of non Euclidean geometries. The fifth Euclidean postulate argued; that two lines are parallel if a third one intersects them perpendicularly. Meaning that for each point there is only one line parallel to any other line. This fifth postulate created a path for non-Euclidean geometries; Carl Friedrich Gauss was intrigue by his postulate and along with other mathematicians was able to reveal the existence of Non-Euclidean Geometries. Beltramis work, established that apparent straight lines are in fact curved ones. Furthermore, that spherical geometry could appear to be planar and one of his greatest demonstrations, stated that curved space could as well seem Euclidean. It was the work of an other mathematician; Bernhard Riemann, that exposed that the space was not only limited to being curved, but as well multi-dimensional by determining that geometries could have as a ground point Non-Euclidean relationships. Now days the use of the computer in design fields is undoubtedly one of the most embracing and dynamic tool designers have in their workspace. It provides with certain freedom to the designer. What is more important is to comprehend its artificial intelligence as a creative enrichment. The possibility of linking individual computer aided methods in order to work on a 3D - model that can be enhanced with information along the design process and lead us to have a complete data of drawings and analytic simulation, in which we realize how conceivable and buildable is our design.

"Indeed the choice of a representational medium has a huge impact on the character of the design results. The medium is never neutral and external to the work. It constitutes and limits the design issues treated and the universe of possibilities for effective design speculation." [1]The explanation given by Patrick Shumacher clearly states the role of digital architecture in contemporary design. Treating digital influences in architecture opens wide new questions not only for contemporary design, but also to the methods used along the history of architecture. In that way, architecture has been limited and enhanced by it's own representational methods.

The appearance of CAAD(Computer Aided Architectural Design) systems, added a different notion in the moment of designing and constructing architectural and spatial concepts, it has evolved from being a simple tool that copies a traditional design and representation, moving to a medium that offers new possible approaches, the usage of CAAD systems, is not only changing the methodology in which we do architecture, but also alters the architectural language we are employing. CAAD systems works storing geometric objects as numeric data and defines geometry as mathematical functions. Moreover, most of these systems have as a root a Cartesian coordinate system that is based on perpendicular axes (X,Y and Z) meeting in an origin point, enabling a manipulation in 2D and 3D of a space.

1Patrik Schumacher, Birkhauser, London 2004. http://www.patrikschumacher.com/Texts/digitalhadid.htm

Chapter One

Performance Based Design

PERFOMANCE BASED DESIGN

This thesis will focus in an emergent approach to architecture in which building performance is the guiding design principle. This architecture takes in consideration performance, at a higher level or as the same level with for m-making; the employment of digital technologies operates in a quantitative and qualitative performance-based simulation in order to project an inclusive approach to design of the built environment. Performance-based design can be approached very widely —from spatial, social and cultural to merely technical (structural, thermal, acoustical, etc.). One of the most important emphases until the date has been on building performance, which is shaping building design, its processes and practices, by diminishing the distinctions between geometry and analysis, between appearance and performance. The performative dimension is emerging in the architectural discourse and is relate to the advance possibilities of form development that are associated with optimization, simulation and generation of architectural form through a deep analysis in the realm of performance. In architectural field, performance is becoming the guiding design principle and is adopting performance based main concerns for projecting landscapes, cities, buildings and infrastructures. As many other processes used now days in architecture, performance uses digital technology for simulating favorable scenarios in which social, spatial, cultural, ecological, financial and technical perspectives are having an influence and are reaching a inclusive approach into design of the built environment. By merging the design and analysis of architectural projects throughout digital technologies of modeling and simulation, the architect's and engineer's functions are progressively being integrated into a relatively continuous digital collaborative enterprise from the earliest, conceptual stages of design.

In order to talk about performance based design we have to shift the orientation of architectural theory and practice, from what the building is to what the building does, in this way the first one becomes a mean of the second. Next we are going to see two ways of understanding a building in a rough manner; the first one is the result from design and construction techniques and the other represent several practices and ideas. Although, these interpretations seem to explain the building's organization and intention, the essential properties of buildings come in consideration if we pay more attention to buildings performances. The aim of this topic is to unveil how the building is conceived through its operations .For making this evident, constructive and perceptual aspects of the building must be put out of the picture for a while, not because they are deceiving, but because they are normally taken to be flatteringly illustrative, as well as the aesthetic explanations should be suspended. What's intended is to let apart the inquiries about experience, meaning and production that generally occupy the main dissertations about a building. This doesn't mean that architectural practice and theory will be redefined on the basis of using new methods and instruments for predicting the buildings environmental or structural behavior, thoughtfulness to performance will contribute to a new understanding of the ways buildings are conceived. As discussed before, it is important to realize that the evolution of late twentieth century has been imperative in the design processes. For instance in topics as ; mass production, information technology, transportation and the workplace. New concerns will influence the future of architectural and industrial design. If we could characterize the new era, it will be through the changing perception of space and design's new fluidity. Architecture and industrial design are both a reaction to and reflection of the society . Architects elaborate a design taking into account requirements and creating thoughtful solutions.

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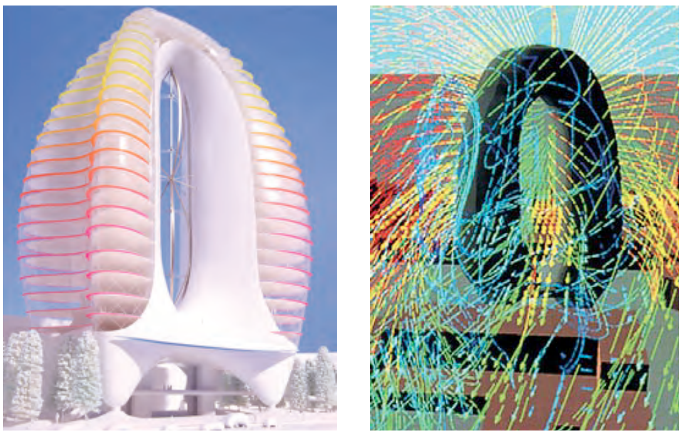
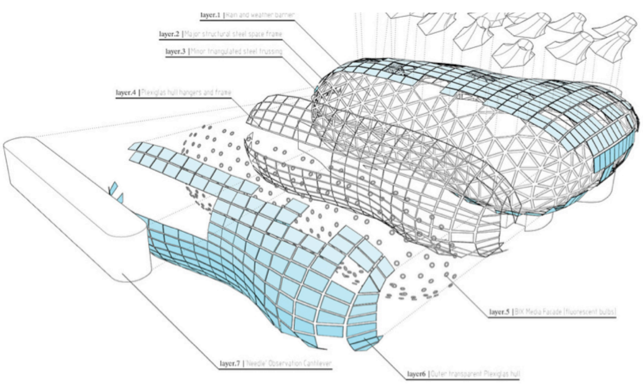


1.1 The CFD analysis of wind flows Project ZED, By:Future Systems Architects. In: Branko Kolarevic, Digital Morphogenesis.



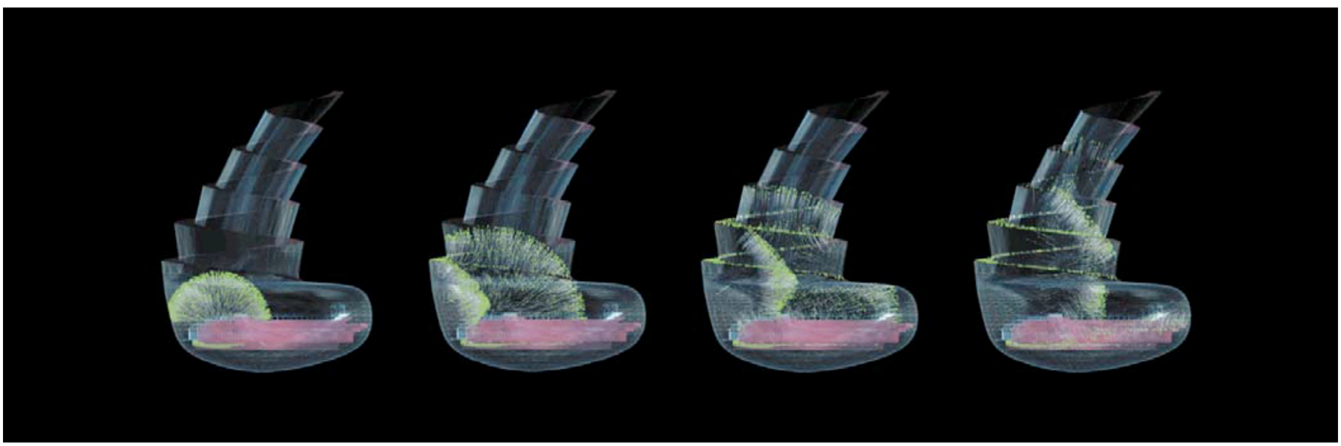
1.2 Exploded structure of Kunsthaus Graz, By: Charliable's In: Flickr.com

In contemporary design, Analytical computational techniques are becoming an imperative tool, not only as an analytical manner of judging a building but, as a projective instrument. Analytical computational techniques based on the finite-element method (FEM), are mostly working through a geometric model that is divided into small, interrelated mesh elements, these elements are used to precisely perform structural, energy and fluid dynamics analyses for buildings no matter their formal intricacy. These kind of quantifiable calculations of specific design propositions can be qualitatively assessed today thanks to the advances in graphic output and visualization techniques. If we superpose several analytical calculations, design alternatives could be compared with relative ease to select a solution that offers ideal performance. As on the finite-element method FEM, there is another method used mainly in airflows within and around the building is the computational fluid dynamics (CFD) software, , fluid flow physics are applied to the digital model of a building to calculate the dynamic behavior of the fluids (air, smoke, water, etc.) Plus the transfer of heat mass, phase change (like the freezing of water), chemical reactions (such as combustion), and stress or deformation of building structure (infire, etc.).

Future Systems, an architectural studio based in London, applied the CFD analysis in its Project ZED, for designing a multiple-use building in London (1995). The design was focused on a self-sufficient building based on its energy needs by integrating photovoltaic cells in the window blinds and a wind turbine located in a vast hole in its center. The curvilinear form in the façade was accordingly designed to diminish the impact of the wind at the buildings boundary and to conduce it towards the turbine at the center. The CFD analysis was crucial in determining the optimal performance of the building envelope.

For the competition of the Kunsthaus in Graz, Austria (2003), Peter Cooks and Colin Fourniers had an initial blobby shape which was altered after evaluating the digital structural analysis, Bollinger + Grohmann engineers from Frankfurt, were able to show that the structural performance could be improved with minor adjustments in the general form.

For the design of the main hollow of the Greater London Authority (GLA) Headquarters (2002), Foster and Partners had to modify several design qualities after engineers from Arup studied the acoustical behavior using an acoustic wave propagation simulation software developed by themselves . Its crucial to mention that the pebble form of the building was developed from optimizing its energy performance by reducing the surface area exposed to direct sunlight. The final blobby form of the building is in fact; a deformed sphere which has a 25% smaller surface area than a cube of identical volume, this formal decision reduced the solar heat gain and heat loss through the buildings skin. The out layer configuration was a direct consequence of the analysis of the sunlight behavior during the year. Fosters studio approached the design of the GLA building in a performative manner inferring in a significant shift in the way blobby forms are perceived. The debate about the highly curvilinear forms that digital appliances showed is changing from an expression of new architectonical aesthetics or a particular cultural and socio-economic moment born out of the digital revolution to a more optimal formal expression for the new ecological consciousness that calls for sustainable building.



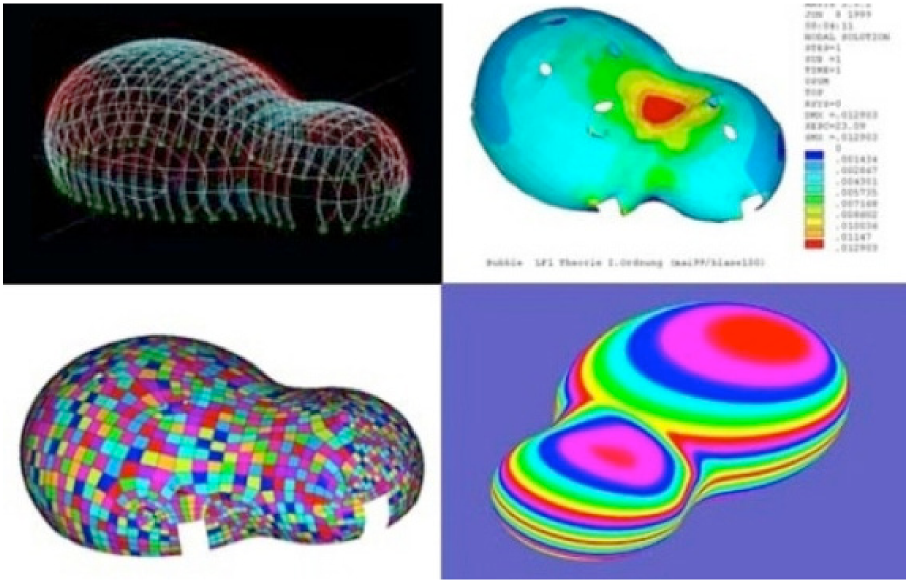
1.3 GLA Headquarters: acoustical studies by: Arup. In: Branko Kolarevic, Digital Morphogenesis.

Considering the futuristic proposal made by Future systems, in which wind turbines are going become feasible elements in buildings, the built environment would accomplish new morphology, and boxes will become as exotic as blobs are considered today. Even though digital technologies, to be more specific the performance based simulations, have allowed the concept of performative architecture possible, both challenges and opportunities make a part in the way these technologies are being hypothesized and used. Most of performative architecture is being used in a passive manner, meaning that is being applied "after the fact", after the building has been articulated. On the other hand, analytical computation could be used to dynamically characterize the buildings in an active fashion, in the same manner as animation software is applied in contemporary architecture.

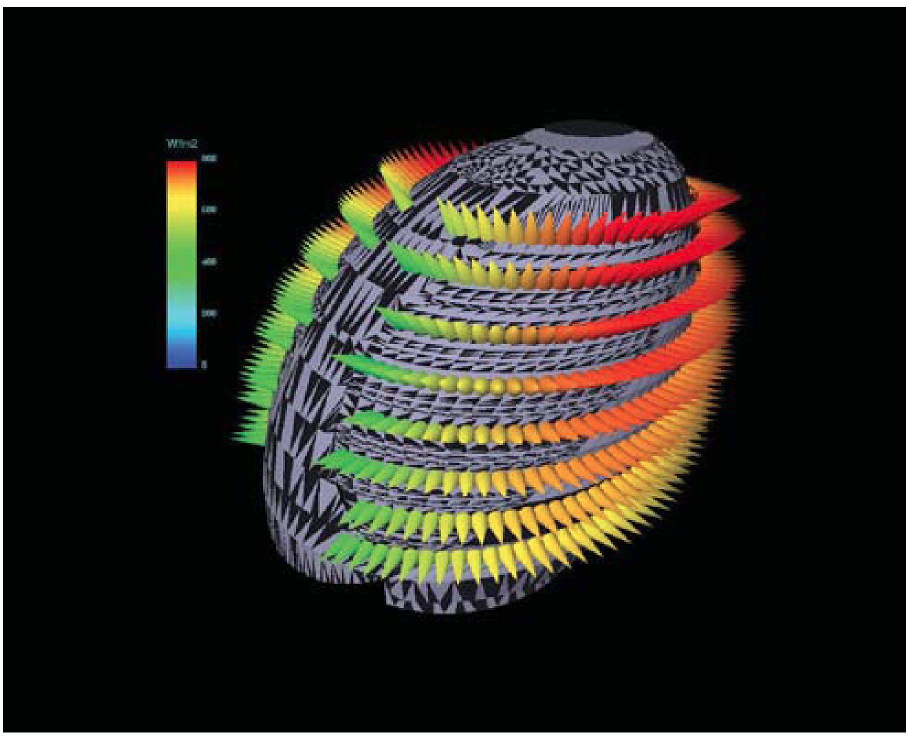
If we take a structured building topology and subjected it to a dynamic transformation that is the result of the computation performance targets, we will have two different performative possibilities, at one end, an unimproved solution and, at the other end, an optimized one , this last one is possible not to be an unacceptable proposition from an esthetic or functional point of views. In that case, second choices could be chosen from the vast range of performative models that satisfy non-quantifiable performative criteria. The analytical software works in the way that preserves the main topological design but will alter dramatically the geometry in response for optimizing certain performance principles (acoustic,thermal, etc.) For instance, if there is a certain geometric arrangement formed of polygonal surfaces, the number of faces, edges, and vertices would remain unaffected- this is an example that the topology wouldn't change-, instead the shapes - the geometry- would be regulated and some limits could be enforced in certain areas. The process of transformation could be taken as an animation, for example starting form the given condition to the optimal one, throughout this process the designer should discover interesting conditions, which are worth to pursue.

FIRST APPROACHES INTO CALCULATING PERFORMANCE

Even though the performative-based design seems to be somehow a recent approximation to architecture, it has been supported for several decades ago by a variety of digital performance analysis and simulation tools. During the late 1960s and early 1970s, a group of academics managed by Thomas Maver in ABACUS (Architecture and Building Aids Computer Unit Strathclyde), developed an idea in which the building design would be determined and dynamically supported by a variety of integrated "performance appraisal aids", operating on computer systems. These movements started more than four decades ago along with computer-aided building design, most of the fundamental concepts and techniques were initiated in the late 1960s and early 1970s. The first case of computer graphics for building evaluation was in 1966, the first bundle for building performance evaluation showed in 1972, the first computer-generated perspective drawings was developed in 1973, we can conclude that the 1970s was a generation in which several computers aids were tying to assure the designer with an estimation feedback on his design schemes, these was helping the architects to acquire precise predictions of the building performance in terms of heat loss, daylight contours, shadow projections and acoustic behavior.



1.4 Performative Analysis of Bubble Project, by: Frannken Arhitects.
In : http://www.franken-architekten.de



1.5 GLA Headquarters: solar studies by: Arup. In: Branko Kolarevic, Digital Morphogen-esis.

Lets talk about PACE (Package for Architectural Computer Evaluation), One of the leading digital performance analysis tools to emerge. This one was build at ABACUS an they introduced it as a "computer-aided appraisal facility for use at strategic stages in architectural design," this particular system focused not on the optimization of a unique parameter of the building but, to produce a cohesive model taking into account the group of evaluation measures. Throughout this decade ,PACE was running along a time-sharing system and the dialogue between human and program was through a teletypewriter terminal. The program was in charge of measuring environmental, costs, spatial and activity performance. For instance, the spatial performance component evaluated site use, to be more exact; plot ratio. Processing the environmental performance gave as an output plant dimensions which would provide acceptable environmental conditions, in view of the heat gain and loss. The program was determined in educating the designer in how to modify geometrical or building information, this iterative work between man and machine led to an optimum state of a design solution. One of the best particularities this program had; was the fact of having a memory who learned the preferences of the user. Therefore, the programs saved the preferential schemes and use them in future calculations. This one was considered a visionary idea, the early advancements in performance-based design software was far ahead of its time either technologically and conceptually. Time has passed and what we are facing right now is a revolutionary approach into performance-based design, as it becomes the forefront of architectural discourse.

DIGITALLY-DRIVEN

Computers consent architects and designers to follow the laws of nature and to being able to explore items in a three dimensional manner with out the restrains of a drawing board or standard manufacturing techniques. Most of developers of computer systems are being made to describe and define space; manufacturers now own computer-aided design/computer-aided manufacturing (CAD/CAM) facilities to accelerate rapid prototyping, letting apart the notion of mass production. In the next projects we will see that most of the elements are defined as unique without any costs implications. Lets analyze the impact of CAD systems in the project that Grimshaw is designing in Australia and in the fourth phase at of Eden project in England.

In Australia, the studio is projecting a city block that fuses the Central Business District and the docklands. Inside that block, in between other buildings, there is a proposal for the new Southern Cross Railway Station (Melbourne, 2002). The performance requirements of the roof were a major contemplation for the railway terminal. Its function relies in protecting and acting as a sunshade, on the other hand they were aesthetics needs due to the skyscrapers around look down on it. Another vital necessity is that of extracting stale air from the diesel trains. One of the solutions provided for solving this problem was the one of using big fans but these ones were not accomplishing a sustainable approach to the project neither a aesthetic one. Instead, a study at the prevailing winds was done. "*The wind effectively sculpts and gives shape to the roof in the same way that it creates dunes in sand or moguls in the snow, these dunes force the air to pass over the roof surface, creating negative pressures to lift out and ventilate the space below, So the roof functions effectively but is also visually interesting.*" In this way the performance principles are the ones in charge of providing a shape for the roof.

1.6 Southern Cross station, by Grimshaw Architects. In: http://grimshaw-architects.com

In England a project in a smaller scale was developed by Grimshaw studio; is called the Eden Project . We are going to talk particularly about the forth phase, this phase comprises a succession of buildings, comprising another biome. One of the buildings is an education center that was thought as low-embodied energy construction building, due to 1,000 school children is the average of visitors per week in order to learn about science and biology, The concept behind the building would express which is the way a tree uses energy. The final design of the building is a tree-like shell form, following a logarithmic geometry in the form of a spiral.

SOLAR DESIGN IN PERFORMANCE BASED DESIGN

The use of solar energy was understood mainly as a way to decrease conventional heating energy in buildings and to generate hot water. Most of the actions taken to project in order to enhance solar design are focus among others; on creating large areas of south-facing covering as well on creating closed and directly insulating north walls. What's more, keeping a strong relationship between the layout of rooms through the orientation of buildings, ensures a favorable relationship between the volume and the surface area of these ones.

The technological advances regarding about heating and hot-water systems improve in such a way that a 60% of hot water requirements in housing can be delivered from solar energy using thermal or storage collectors. On the other hand, in moderate climates, the fact of over insulation leads to cooling problems in the summer, especially in certain buildings as administration buildings. If we have a close look to the energy consumption of a random office building we get that less than the 10% of the overall energy consumption is attributable to heating. Now if we have a look to the energy the building requires for cooling it varies between the 10 and 20%; on an average point of view cooling needs three times more primary energy per KW hour as heating. Today, the fact that designers can have a straight comparison about the g values (the total energy-transmittance value through a material) is extremely useful data in the construction of external walls, allowing buildings to behave accordingly to changes in the weather. If we take another approach and try to reduce the areas of glazing, the amount of daylight that will enter the building will decrease as well, therefore the percentage of artificial lighting needed will increase. In Europe, the average of energy required for artificially light office and administration buildings oscillates the 30%. From a long time Computer software have been available for accurately simulate and process data in diverse areas of construction, as the thermal or lighting balance of buildings. Advancements in these areas are on constant experimentation, most common areas include; vacuum thermal insulation, new types of glass that react depending in the changing requirements of the insulation, for example: the switchable glass that works as an inert-gas filling and with U values of around 1.0, the electrochromic and thermotropic glass and the presence of ventilation components that contain a solar preheating facility.

The collection of the environmental energy can be assessed in various manners, passing from ventilation, natural lighting and heating to the generation of electricity via photovoltaic systems. It is important to realize that the conditions transform according with the season and the building will encounter conflicting needs. What's more, most of this problems are being solved by "intelligent building" systems that in order to respond to changing conditions and functions such as; the operation of sunscreen blinds, co-ordination of day lighting, complementary artificial lighting consume, heat generation, ventilation flaps, and humidifiers. The real problem is that these types of controls are powered electrically, therefore the systems become technically vulnerable, inducing to higher construction costs.

RESEARCH TOOLS

In order to enhance the performance simulation of a building, a specific expertise is needed for converging the design, engineering, operation, construction and management of buildings. It coalesces diverse disciplines resources, including, mathematics, material science, physics and human behavior. The purpose of the simulation is to predict the behavior of a building from its conception to its execution. The basis of the fundamental work on building performance simulation was develop few decades ago by working mainly on algorithms and predictions. Now days simulation tools are broadly available influencing in a huge how buildings are designed, analyzed and constructed. The softwares have concentrate in generating environments focus on providing user-friendly interfaces whilst allowing for flexibility in modeling and precision. The structure of the simulation includes algorithm advances, data managing and interfacing. These kind of simulations as we said before, are based on algorithms, which have been designed to predict answers to domain-based questions, as thermal, lighting or structural problems. These on going algorithms are under a rapid expansion in the areas of code validation, uncertainties and efficiency of representations. Mostly, in an effort to shift from a pre-established manner of using these tools as analytical, into a tool that can analyze and synthesize data. This inquiry is originated from the idea that digital simulation tools can be used to assist performance-driven design using optimization and partial automation.

CATEGORIES

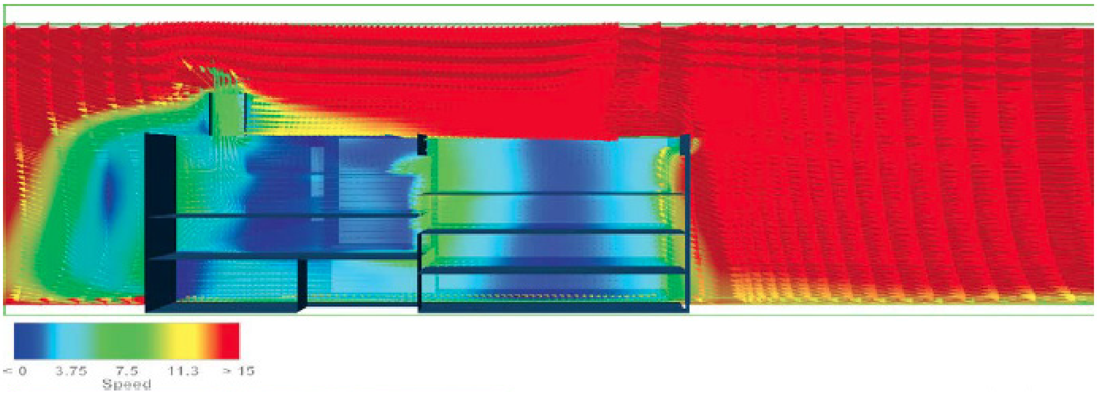
Several tools have been developed to envisage the performance of buildings in particular areas as specific examples we have to talk about the structures, thermal flows, lighting, acoustics etc. As we know different problems can not be approached by the same algorithms that's why, a selection of computational simulation tools exist. These tools have a strong range varying from simple approximate performance to the a very accurate. As the digital technologies became widespread, the use of CFD began to increase between not only the engineers' studios, but designers started to involve this kind of studies in their works. CFD works in applying numerical techniques for solving Navier-Stokes equations for fluid fields and it provides a method to solve the conservation equations for mass, momentum and thermal energy. The role CFD has in the buildings is different areas. For instance, in natural ventilation design,building material emissions for indoor air-quality assessment, and complex flows of fire and smoke in buildings.

Under the scope of CFD, it is possible to use different parameters for predicting different situation models. Even though, it's a well know methodology for studying noise, smoke, fire and in general fluids behavior. CFD is consider to be under development and the importance in having validation procedures is high, in order to verify the CFD results. What's more, CFD software are becoming more popular for building professionals , but we have to remember that it requires a deeper understanding about fluid mechanics to set up a simulation model and manipulate its conditions to interpret the results.

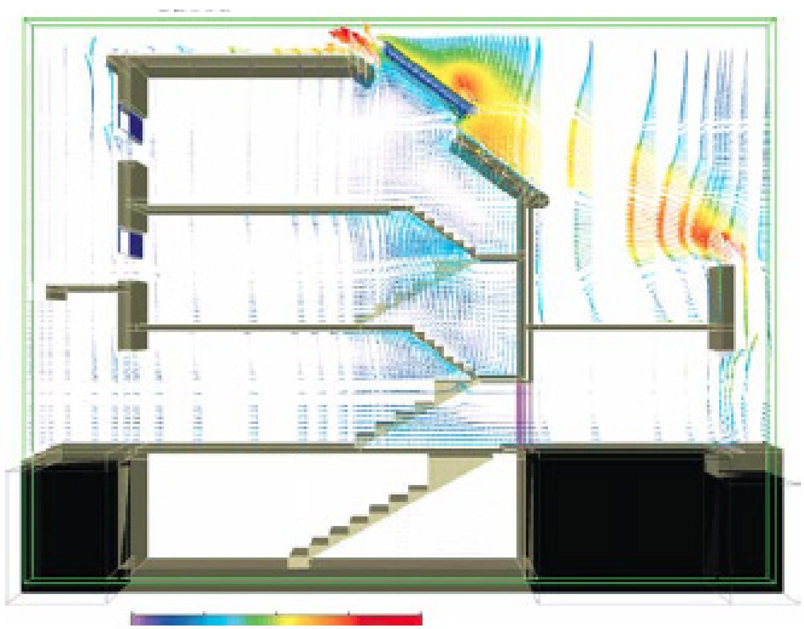
PERFORMANCE PROCEDURES AND TECHNIQUES

Lets discuss about the methods and techniques incorporated to increase the utility of the simulation in the design, there are several factors involved in the development that concern with the performance based simulation for architectural design, among them we find decision support environments and optimization in the models, as well as user-friendly interfaces combined with visualization techniques, this kind of decision support environments were developed two decades ago. In this dissertation computational algorithms play an important role, this ones were developed for systems that aided designers in their approach by offering a guidance throughout an advice for optimization using emergent Artificial Intelligence procedures. These problem-solving methods were investigated for their potential in users that relate with them in a skillful and non skillful manner to implement and interpret simulations. Their influence has been noteworthy in starting the use of computational techniques to elucidate performance-based decision-making problems. This approach to design is governed by the idea that design is a goal-oriented decision making model, where goals are stated by required performance values.

Performance simulation had to work hand by hand with the applicability of specific algorithms with respect to their efficiency. The stochastic technique and genetic algorithms have been a repetitive methodology that has been applied to a extensive variety of problems, including thermal and lighting performance in buildings. As genetic algorithms, gradient-based and derivative-free methods are playing a part in these cases of performance simulation, these last ones perform very well for issues relating simulation for noise. Now lets have a look to the strategies that are combining more than one method, an example of this methodology is merging genetic algorithms and pattern explorations to originate a hybrid method to diminish computational time in problems involving expensive simulations. While optimization algorithms have been used in a variety of ways in building simulation, their potential have not been exploited at a full potential yet. What we have found out about design optimization is that it has been used to improve building performance. In the next chapter we will see several examples.



1.7 CFD simulation and analysis for the PennDesign building by: Ali Malkawi. In: Performative Architecture.



1.8 CFD simulation and analysis of Civic House for University of Pennsylvania, by: Ali Malkawi. In: Performative Architecture.

As important to simulation tool development are issues related to the relations between the user and the problems the tools need to solve. This relation will conduce the development to a certain direction, is clear that most of the simulation tools are analysis-based and assist a diversity of design activities. The core of the improvement in simulation tools, is based in the fact that these tools shift from analysis to performance-based active design which is an area that is growing at the same pace with the improvement of digital tools. Including such concerns has the potential to permit active design support to happen. Taking benefit of these improvements, in addition to automating some of the simulation processes, will provide simulation tools a superior position in design activities.

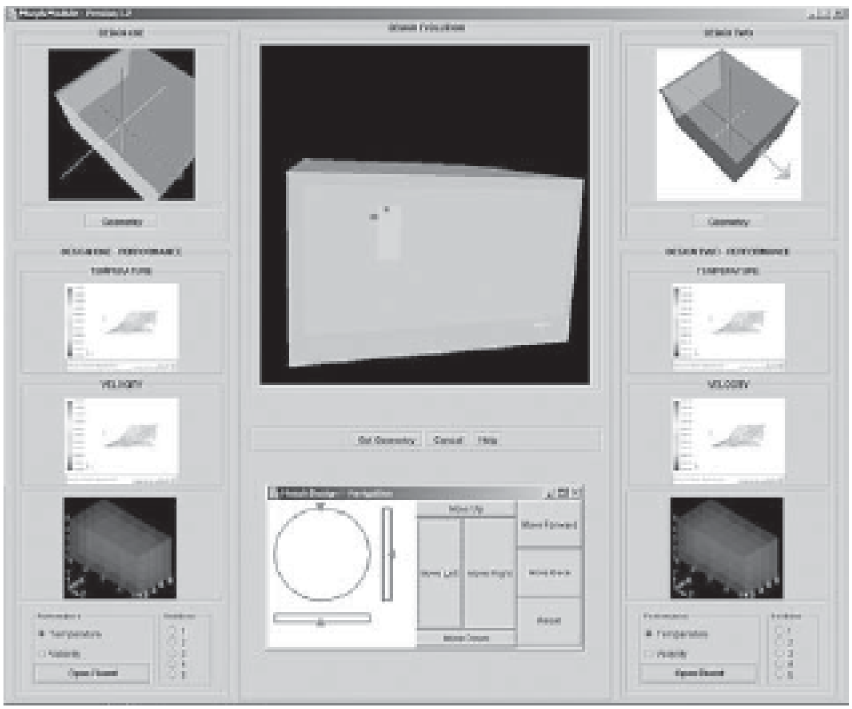
As an example of these relations, lets have a look into a research project that combined computational fluid dynamics and genetic algorithms. The project makes use of thermal and ventilation performance criteria as a methodology to generate creative design selections. This process involves a deep knowledge about the problem and substantial proficiency, every design modification made to space geometry or its boundaries, obliges to the user to redefine the model, re-mesh and consequently re-compute the airflow. The exchange between altered design transformations generally remains unnoticed because of the intricacy of the model.

Because the design space is arduous to explore methodically, solutions can be unnoticed. That's were, visualization is used as a solution to such a problem. Evolutionary algorithms have conventionally been applied to elucidate optimization problems. Furthermore, they started being used as a design aid. The method is a "generate-and-test" approach that resembles well to the techniques for design and evaluation in the design process. In this kind of based generative process, design exemplifications are quantified as a set of parameters and as a corresponding group of restrictions. Generative design defines an extensive class of design in which the design examples are created mechanically from a high-level specification.

Design advancements can be used as a support in inspiring the designer role as a creator. The benefit from this approach is the conception of diverse phases of the state of space that work in parallel with performance goals and increase the possibility for discovering a variation in the possible solutions by postulating a wider search space for designers to interact.

The project showed the potential of studying and visualizing the design progression and its form origination, based on predefined inputs of performance objectives. As well, is clear how a performance-based design evolution model consents a well-organized exploration of design options by using a four-level approach: design evolution, performance evaluation, morph visualization and design evaluation. The role of the genetic algorithms relies in generating the shapes accordingly with the design instances, for every design modification, a CFD analysis is run mechanically to calculate the thermal and ventilation efficiency performance, and the results are loop back into the genetic algorithmic component. This process operates in a loop, pending on the best designs solutions to be returned. To get a clear idea on the system's solutions and in between instances as the solution is evolving, the system is integrated with a morphing module. This component permits to the diverse examples of designs to be envisioned along with their performance, in this way the user can enhance its potential for design discovery and to provide assistance within the design process.

Throughout morphing, users can intervene in order to stop the simulation process and select an example based on its form. What's more, this design example can then be calculated for its performance using an incorporated CFD engine.In the moment we incorporate an optimization component that creates various examples of design with a morphing module, the system is capable to deliver an example of continuous evolution of optimization. While reversing the sequence from the design-analysis paradigm to a performance-based simulation-decision support paradigm has been investigated, a clear shift has not been done yet. One of the major complains that these kind of tools receive, is the fact of being multidisciplinary, meaning that the building industry needs a high level of professional experts in order to make a comprehensive lecture of the digital design.



1.9 Performance based Design Evolution Software Interface. by: Ali Malkawi. In: Performative Architecture.

ENGINEERING PERFORMANCE BASED DESIGN

One of the biggest premises for todays engineers about performance based design, involves in investigating for techniques for moving computational tools from behaving as means of testing design ideas to being essential parts of the design process, parts that can feed design input quickly and iteratively.

Examplars

Lets talk about the performance based design in engineering fields, for instance, in the structural engineering field, finite element programs have been used as the principal computational tool for the past thirty years. Current improvements in graphic and CAD modeling software have helped to the progress in the appearing of more complex structural forms, these finite element programs have become commercial and have kept up with the pace of the contemporary architectural language. It is worth to name certain performance-based software developed by some of the engineering firms aimed at more specialized areas of structural engineering, in the case of Buro Happold; they were able to develop a non-linear finite element program, called TENSYL, for analyzing cable nets and tensile structures, these types of structures become the perfect example of performance-based structural design. When we think about the form of these structures, there is an inverse process in the manner of designing. Meaning that, the general rule for projecting tensile structures are form found from boundary conditions with surfaces that are calculated between these boundary inputs. The surfaces that are being generated are considered non-geometrical, due to they do not follow any mathematical formulae. Structures as this became economically developable with the support of computational models for load analysis and surface patterning for fabrication. TENSYL software evolved into a powerful instrument for shapeless structures and to perform geometrical analysis, this can be seen on the project developed in Stuttgart, the architectural team explored really intricate physical models, these ones were reconstructed computationally for the first stage of analysis for the project.

In this process, a tensile mesh model approach was done in order to form-found and develop shell surfaces. The idea behind these shells is that they could work under compression and make an extension of the roof of the major train station in Stuttgart, Germany. These shells were design with openings to permit light diffusion from the superior level that is park down into the new track levels.

One of the important factors in managing amorphous forms, it's their economical building construction costs. Performance based design has made investigations to benefit this fact. The use of principal curvatures is a technique to economically "diagram" a curving surface into flat planes, in this way there is not necessity to use expensive curved glass or other curve elements for cladding. Lets see another example from Buro Happold firm, which established an exclusive software routine to apply this method efficiently on a variety of surface structure projects. For the design of a 20,000 square foot glass canopy project in Japan, in this project, the structural system was planned to assist the principal curvature lines in order to achieve flat panels over the curving structure surface. This firm has done amazing improvements not only in the construction of digital tools, but as a cohesive design, their experimentation with the materials represent several of the greatest advances in performance-based design, due to design processes and projects can be developed precisely to suit the material's characteristics. In this particular project and other ones like the Japanese Pavilion in Hanover, Germany they have mastered the use of standard paper or cardboard in construction. This material has compressive strength alongside the lines of wood; it has some restrictions in application by its overall rigidity and a propensity to lose its position with time. On the other hand, being a recyclable material and one obtainable economically throughout the world like spiral wound tubes, it becomes an eye-catching material for temporary structures.

A performance-based approach was essential, because the cardboard material has no established prescriptive design guidelines. Throughout intensive testing that in-

1.10 Tensile Structure by: FLT studio. In : http://estruturasarticulaveis.com

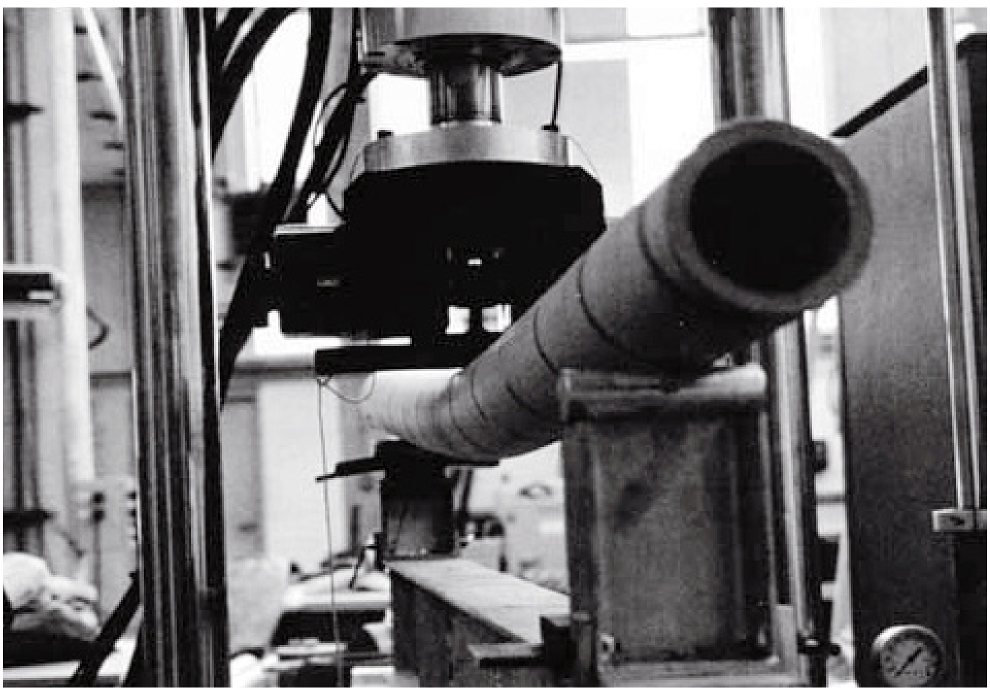
1.11 Cable net model, by Frei Otto. In: http://researchbank.rmit.edu.au

In the case of the biomedical research facility located at the University of Michigan, the CFD modeling was used in the large lobby space and double façade cavity wall system for emphasize the environmental strategies desiged by the architectural design team for the project. Until this point, we have checked energy modeling, CFD, thermal and lighting these kind of simulations are becoming indispensable for low energy and high-performance building system design. Lets have a look to the environmental effects in different scales, both a micro and macro level, can now be examined and are capable to structure and notify for critical design decisions. In the next graphic, for the BBC White City project in London, a pollution dispersion modeling is employed, the CFD simulation evaluated the pollution produced by the campus power equipment. In this procedure, studies about light pollution were shown on the site.

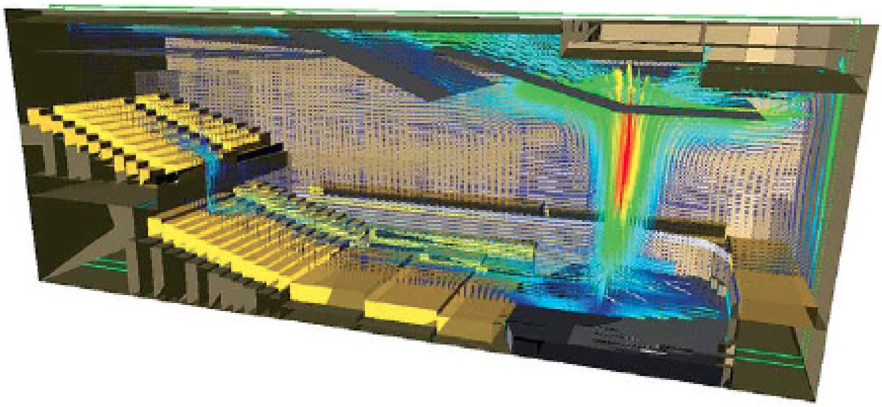
Between all this digital tools, CAM tools are being correlated with advanced fabrication solutions to building mechanisms. The continuous advances in architectural modeling tools and the more risky geometrical proposals, have been insisting in the progression of CAD/CAM technologies. The work of a new generation of architects is now getting more used to rapid prototyping, 3D printing and several of new CAD/CAM systems that were at first developed for industrial design requests, mainly in the auto industry. These tools involve not only the construction of a product but comprise as well the mindset of the new designers, it is undeniable that CAD/CAM developments for large scale buildings are gaining significant importance. Engineering designers who are able to relate with these programs by making a global use of these fabrication processes to update their designs, will go even further in the use of performance-based building design in the future. As shown in the Gates head Music Centre's roof, this structure was developed parametrically to exploit the use of steadily radial primary and secondary steel framing. Likewise, in the British Museum's roof which exemplifies an example where CAM not only was used for aesthetic, neither structural reasons, but for economical ones.

As exposed in the beginning of this thesis, the performance-based design is not only attached to technical and quantifiable issues of a building or project. Simulation tools concerning human behavior are now appropriately useful in developing and examining new design strategies for public spaces. People movement software replicates individuals and response times to life safety events or situations high concern in public areas as the morning rush hour: these are calculated having in consideration of the building design and layout. In the Arsenal Stadium project is clearly exemplified the use of people flow modeling for crowd control. The high interest in these performance based design tools relies in the fact that they are in a very early stage of development, we could say at version 1.0. of Computational power according with Moore's law. If engineers and designers continue at this pace of computational modeling, this will allow more design feedback loops and will lead to a more comprehensive design for building and infrastructural teams.

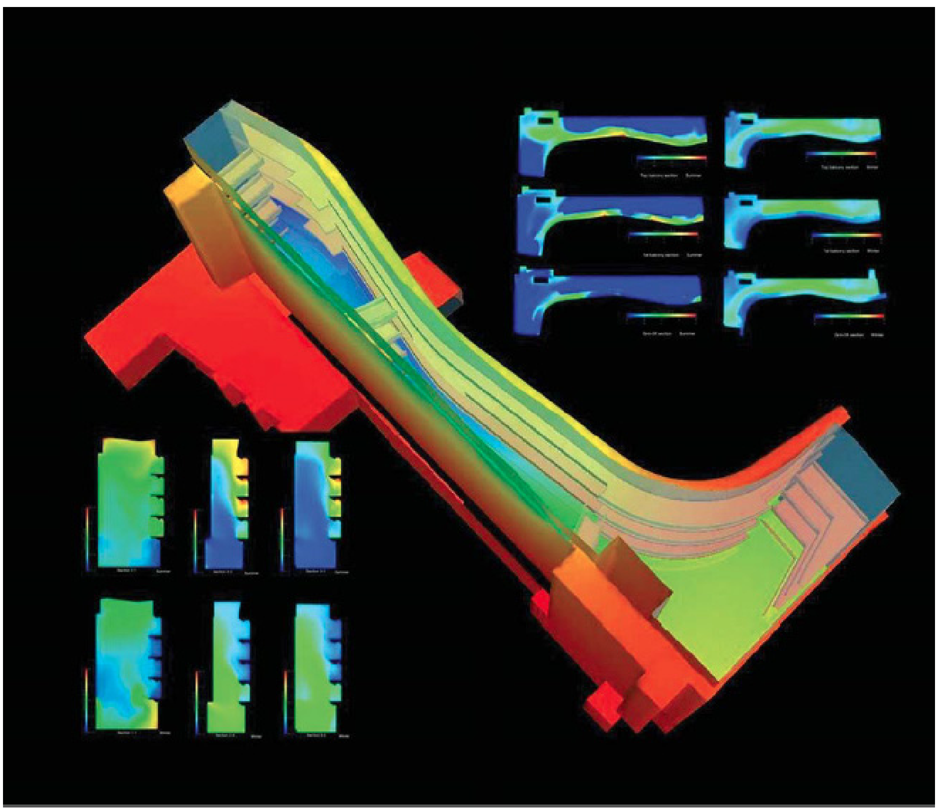
1.12 Japanese Pavilion, Hanover, Germany , by : Shigeru Ban Architects. In : Performative Architecture.



1.13 Testing of cardboard tubes to establish design guidelines for the use of the material in construction, by : Shigeru Ban. In : Performative Architecture.



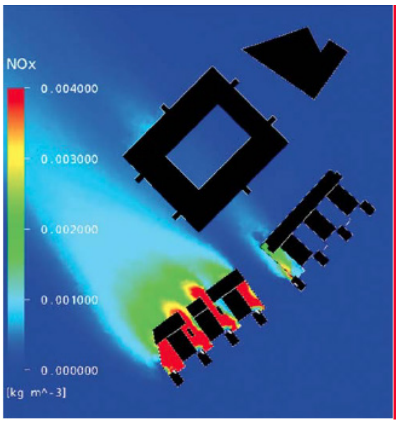
1.14 The CFD model showing relative air velocities in the displacement ventilation system by: architect Nicholas Grimshaw and Partners. In : Performative Architecture.



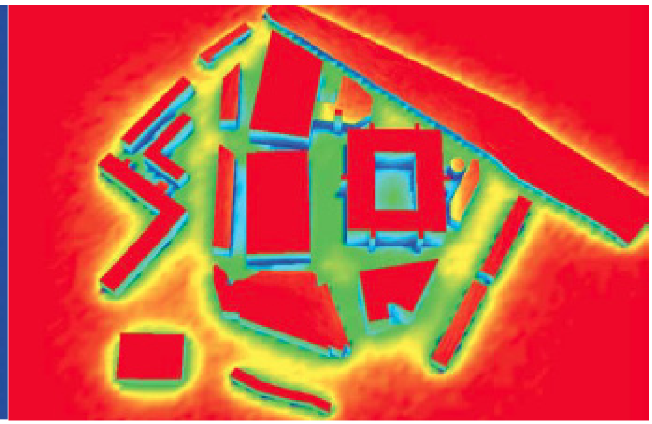
1.15 CFD models for lobby winter and summer environmental modeling in The University of Michigan Biomedical Research Building by : Craig Shwitter. In : Performative Architecture.

To sum up, computational tools are achieving stages in a diversity of uses and in concrete applications in several ranges of building engineering design are pushing the limits of intricacy in architecture and urban infrastructure. The experiment in the use of these tools will rely in adapting them to specific problems, and coherently ask ourselves how well adapted are they into the design process.

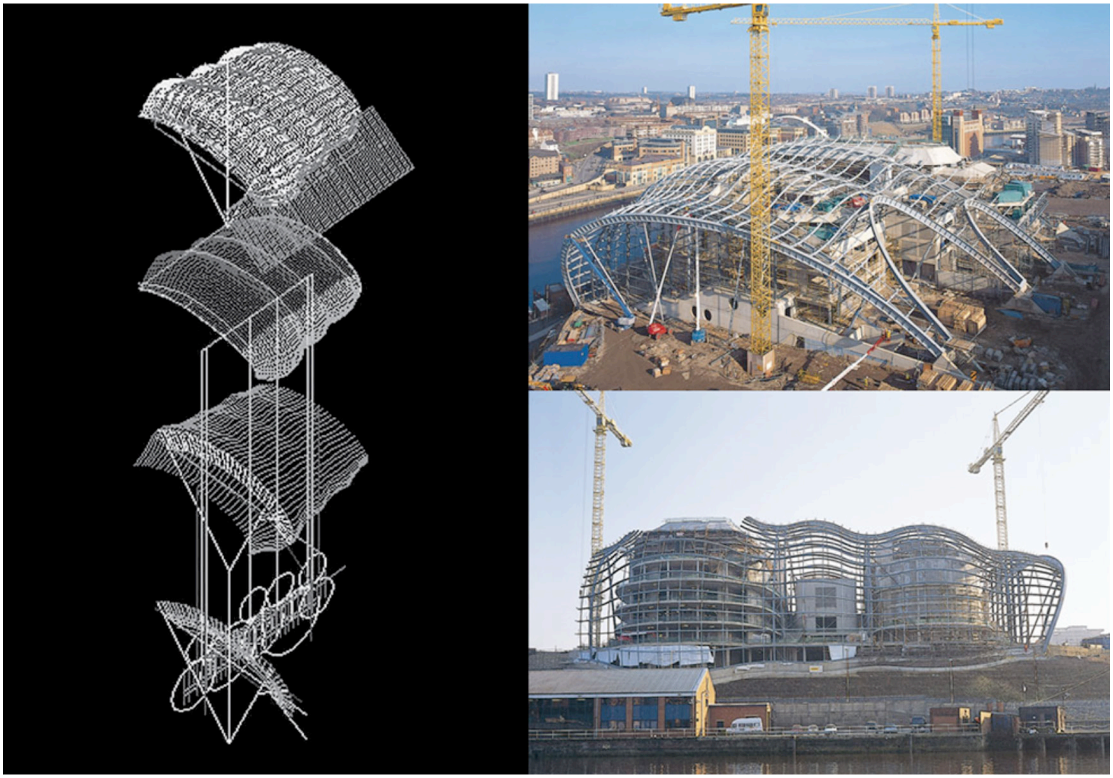
On the other hand, we have to be clear on the fact that computational tools do not offer solutions for design, They serve as support, and it is the obligation of the designer to warrant quality in the projects and coherence way of thinking during in the design process. Conclusively, it must be obvious that today's performance-based methodology may transform in a future prescriptive recipe for solving a design task. As designers we should embrace and accept the constant shifting processes in the world and avoiding resisting this critical process of development of the built environment, therefore this will lead us to avoid the rigid manner of solving design tasks and to think out of the box, by doing this we will assert in more human quality designs.



1.16 CFD model of external air pollution on site, by: architect Allies and Morrison. In : Digital Morphogenesis.


1.17 Light pollution on site, by: architect Allies and Morrison. In : Digital Morphogenesis.

1.18 Arsenal Stadium, crowd flow modeling by : architect HOK . In : Digital Morphogenesis.



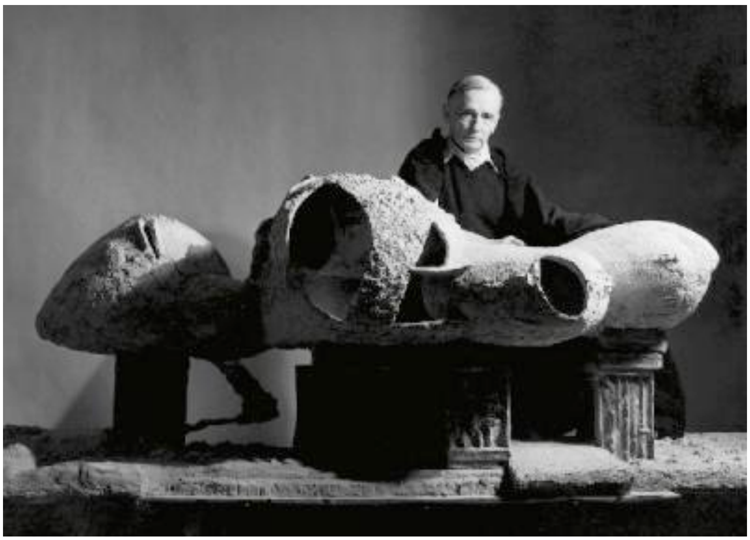
1.19 Parametric modeling for roof structure to provide economy in Gateshead Music Centre, by : architect Foster and Partners. In : Performative Architecture.

NON STANDART STRUCTURAL DESIGN

Lets have a look into structural engineering from a performance-based architectural design environment. Instead of designing and producing the so-called “free-form” or “non-standard” architectures. Calling the architecture of complex geometries as “freeform” is rather divisive because the expression tends to simplify the conceptual and intellectual complexity of lately established digitally driven procedures of form generation. The term; “non-standard architecture” was coined by the curators at Centre Pompidou in Paris to indicate to the architectural pieces expressing the innovative formal freedom. Either way “freeform” or “non-standard,” during the last years the architectural environment has seen an amount of completed projects with complex geometries that are manifesting a shift from traditional formal principles in architecture, therefore requesting novel methodologies to structural design and engineering, in which performance-based design and digital workflow are interlaced. The comparison between the biomorphic structures discovered in nature and the material certainties of tectonic languages in building shows up an obvious basic difference that is related with the fact that there are no straight lines and rectangular geometries in nature. The reason behind this is that the form generation processes in nature are founded on the guidelines of evolution and are enhanced for adaptability in the natural environment. Instead, formal and tectonic definitions in architecture are done by the capabilities of the technical production; this has a strong relation with the available technologies in a given era. For example, with industrialization, the technical options of production amplified significantly, therefore allowing the departures from basic geometries possible in architecture.

These geometric shifts often overlapped with the development of new techniques and materials. This relationship is historically evident; e.g., in the 1950s, 1960s and early 1970s, advances in concrete and later plastics and textiles stimulated architects and engineers to progress from Pythagorean geometries and to manipulate form in a minus reserved geometric way. The most recognized architectural examples are the filmy shell structures of Felix Candela, the structurally logical decoration of the Palazetto dello Sport in Rome built in 1957 by Pier Luigi Nervi Eero Saarinen's concrete sculptural forms for the TWA Terminal in New York, completed in 1962, or Matti Suuronen's ideal plastic visualization for "tomorrow's living" called the Futuro House. All of these architectural projects show and put in evidence the technical potential of this period of time and above all of this they represent the spirit of the time, comparable with Frei Otto's lightweight tent- and cable-net structures which gotten their highest point in the Munich Stadium for the Olympic Games in 1972 .

Is worth it to realize that this "formal freedom" that was developed in the period of time from 1950 to early 1970s was not fully exploited because of the absence of high-performance hardware and software tools in design development and manufacturing. In the work of Frei Otto or Heinz Isler experiments aimed at form finding were done with scaled physical models, the forms they proposed were done throughout a model-based form finding process which were structurally enhanced by analyzing and studying the rules of physics.



1.20 Endless House, by : architect Frederick Kiesler.
In : http://archdaily.com

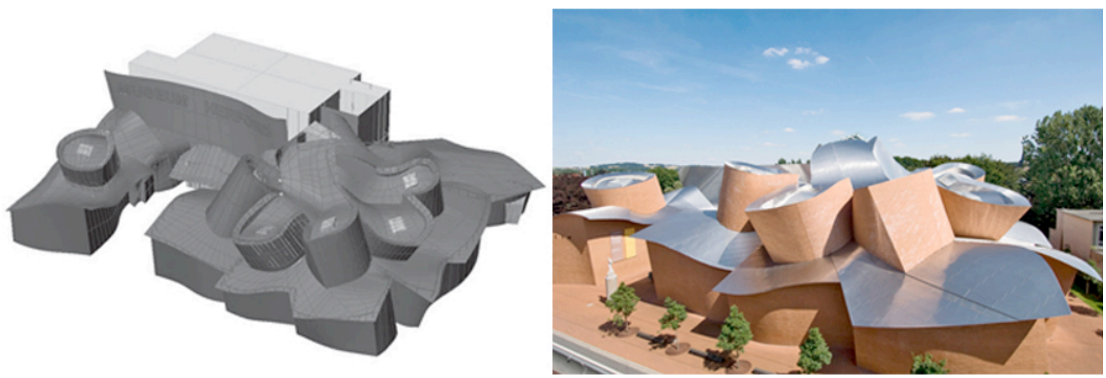
This was a straight up forward manner to understanding the intrinsic relation between structure and form. Instead, in the 1960s nontechnical issues inspired Frederick Kiesler an Austrian-American architect, even though during the conceptualization of an architectural project searching for a solution a structurally optimized and geometrically clearly defined form is a fundamental condition for building, Kiesler was not concerned in outlining forms in a geometrically precise method that followed physical logic.

For instance in his design of "The Endless House" his several free hand sketches represented a way of visualizing his concepts about the form, his designs were considered to be the "biomorphic answer and antithesis of the cubistic architecture of modernists." Under his perspective form didn't follow function, instead, form follows vision and vision follows reality. Just as a sculptor in order to express his complex spatial ideas, he approached the design by physically modeling, as he was doing an art piece. In his system of approach to the "Endless House" he was not concerned by structural optimization, but to proportioning issues that were taking the scale of human beings in the natural as the design instrument.

Architecture is experiencing a revitalization of free forms, as we have discussed before architects today are formally less inhibited, this has a strong relation with the improvements in computer technology. In the case of Kiesler, his generation process of developing sketches and physical models were not interrelated, even though they had the same starting point the geometrical output was not accurately the same. In today's architecture, a digital model that associates design and manufacturing procedures became a general and basic circumstance for assembling freeform architectures. The method Digital models are being generated is highly correlated with the design process, which varies from architect to architect or even from project to project. Furthermore, each geometrically intricate project exemplifies particular tasks for structural design and as a consequence in different digital working processes, lets analyze some projects that involve these kind of procedures.

MARTA HERFORD MUSEUM

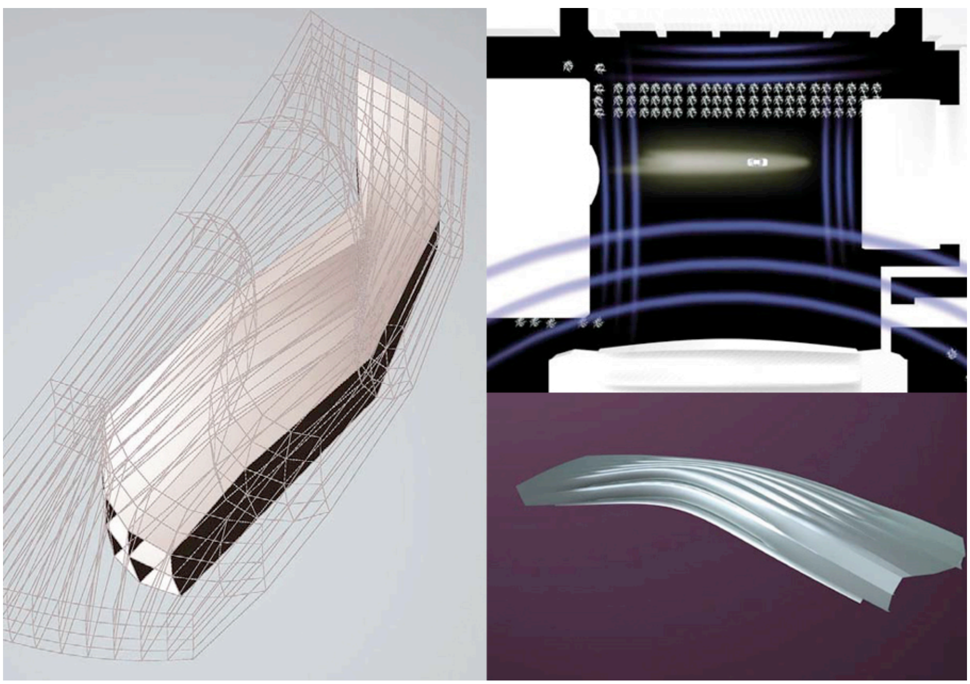
In the case of Frank O. Gehry's design for the Museum in Herford, Germany, a completely different approach was done. The design approach started manually, building a series of physical models, which later on where three-dimensionally digitalized in the computer aided design (CAD) environment of CATIA10. In this way the group of architects were able to correct and check how the shape was behaving in the context and with the program needed. Gehry normally focuses on the properties of the exterior surface with the interior spaces, and most of his work is done on physical models to validate that the original design purpose is met. Once the CAD-corrects the data, this enables the designers to work on more accurate physical models; some of them become sketch models and some others are more detailed. They are often manufactured to investigate the implementation of the general shaping scheme in projects. Gehry's form-finding is a repetitive process in which form modifications are programmatically determined.



1.21 M.art.A. Museum, Digital model & building by : architect Frank O. Ghery.
In : http://researchbank.rmit.edu.au

DYNAFORM

This is the name for the BMW pavilion project proposed by Bernhard Franken for the 2001 International Motor Show in Frankfurt. The architect and his team approached the project by using computational tools to create the architectural form; for this project there wasn't predetermined formal idea at the beginning of the design process. The design process started as a parametric approach, the client wanted to establish a clear message for the exhibition, so they could introduce their new "7" series. The conception of the pavilion started in the moment in which Franken architects read the context in which the pavilion was going to be fixed, in order to pick up sit specific parameters and translate this kind of data into a software tool, that was in charge of visualize it as forces using Maya animation software. The digital design process started with a three dimensional matrix (3D) that was molded referring to the virtual forces of a driving car and the relationship with the contiguous buildings on the site, which had a tremendous impact on the shape through a sequence of specifically designed force fields. A crucial animation defined the modeling process that was relying in a time-based (4D) visualization, this initial shape given by the software was then deformed and manipulated, until in a laborious procedure an architectural form was defined by testing the generative process, an approximation of the shape was done and the general form was then corrected for geometrical errors and established the 3D "master geometry" of the project. That "master geometry" offered a base dimensional indicator for all the people involved throughout the design development and construction.



1.22 Form generation process in Dynaform project, by : Bernhard Franken. In : http://www.franken-architekten.de/

KUNSTHAUS GRAZ

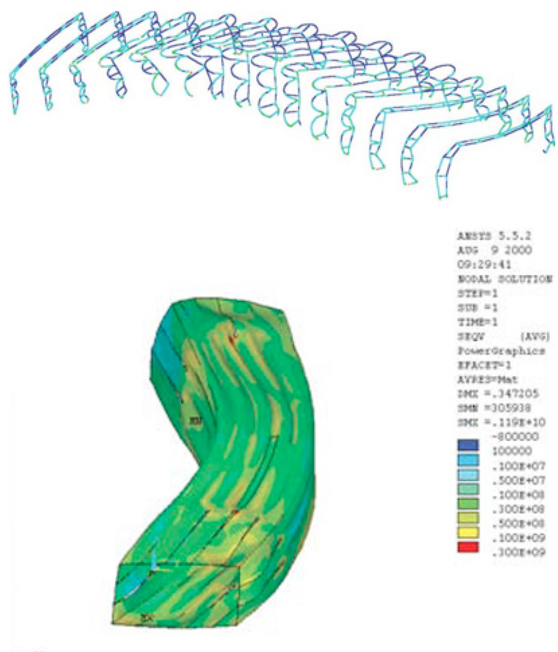
For the Kunsthaus Graz, Austria. Peter Cook's and Colin Fournier's took a completely different approach from the ones described above, for facing the competition their first approach was to hand model their proposal, the next step was focused on making a 3D scan of this model, but they realized that in order to improve the general form in terms of structure and materials, the project was aimed to a parallel work between architects and engineers which decided to produce a new 3D digital model from the beginning using Rhinoceros 3D modeling software. They were trying to follow the original shape that was planned initially, at the end the digital 3D model was built without taken any digitized data from the physical models, which is a similar process used in Gehry's office, as we said earlier. The digital design model was done to apprehend the design intentions of the first scheme and permitted to enhance the form along the design process with respect to the structural behavior, as well its geometrical stiffness, and to manage some of the manufacturing issues. If we compare this approach to the other ones we have checked, there is a significant difference from the one used by Bernhard Franken where the digitally-generated form was demarcated as a "master geometry," implicating that later in the structural design it was not feasible to adjust the form geometrically by altering the shape.

1.23 Building & Physical model of Kunsthaus Graz, by : Peter Cook Architects. In : http:// spacelab.co.uk

STRUCTURAL DESIGN

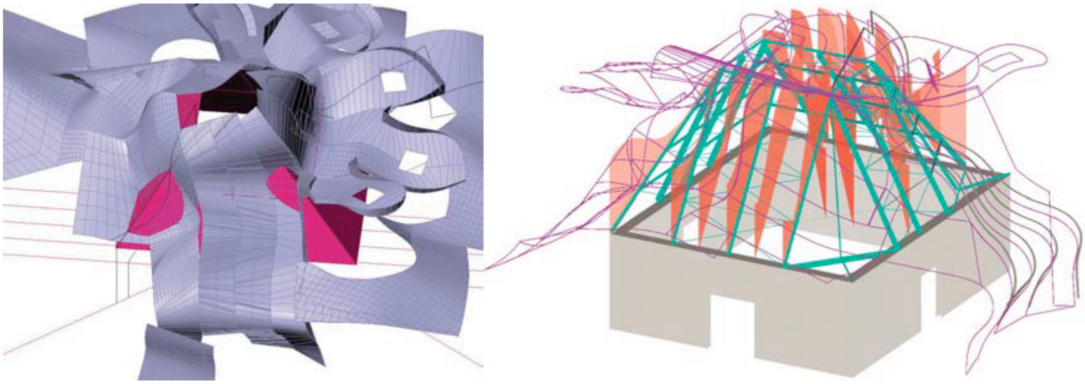
Structural design deliberates about the issues of passing from a geometrical model to a structural system in buildings, to clarify it even better, the structural design merges the formal architectural idea with the rules of the weight flows among others. But lets discuss the different approaches we have analyze until this point and in which way they are influencing in the general conception of the project. Until this point we have realize that the design processes in the analytical software tools operated by the engineers and the 3D design environments manipulated by architects do not generally share a mutual digital databank organization. Therefore, one of the major concerns for engineers is in developing data "post-processing methods" that mechanize and accelerate the geometrical data feedback. Storing geometry manually is not useful and takes a lot of time for highly intricate shaped structures. Being capable to import data files in an exact manner and rapidly, allows engineers to apply finite element and spatial vector software to design tasks that need to be solved through the first design stages. Lets go back to discuss Dynaform project, in this project a single layer skin demarcated the produced form what we have called the "master geometry."

They were two things that were not specified; the material and the thickness of it, once the "master geometry " was fixed, it wasn't possible to enhance the structure geometrically throughout variations of the general shape. Bending moments and local forces had to be acknowledged since structural optimization of the general shape would induce in a contradictory design approach into question. In its place, the purpose was to sustain the meaning of architecture to convey forces into a dynamic balance and to be cohesive in the idea that the form is only an unmoving instance from several sequences of probable geometric constructs. The outcome at the end resulted in a structural system that wasn't enhanced in Dynaform. In order to face non- standard structures, designers couldn't relate in a strong manner with these forms, because there wasn't a strong contextual experience on them, that's why there were two options to construct the form and enrich the structure: It could be as a design system of linear or curvilinear structural elements that would sustain a secondary and non-structural skin, the second option could be to consider the skin itself to be conceived as the primary load-bearing system and would have to transform into a surface-structure with shell-like performance. So as to make a decision concerning which option to assume was determined by a number of revisions of the different approaches; the final structural design was worked side by side in close teamwork with the architects. They counted with a critical few amount of time; therefore the argument to distinct the structure and the skin was chosen by projecting a primary load-bearing structure of soldered steel frames and a secondary pre-tensioned membrane layer. For the Gehry's project, the starting point was the digital geometric model of the outer and inner surfaces; in this particular case the space that was in between these two surfaces had to contain the structure and all necessary mechanical systems. The load-bearing structure was defined as a sequence of steel frames that are covert from the observers view and consequently became irrelevant for the architectural language of the building.



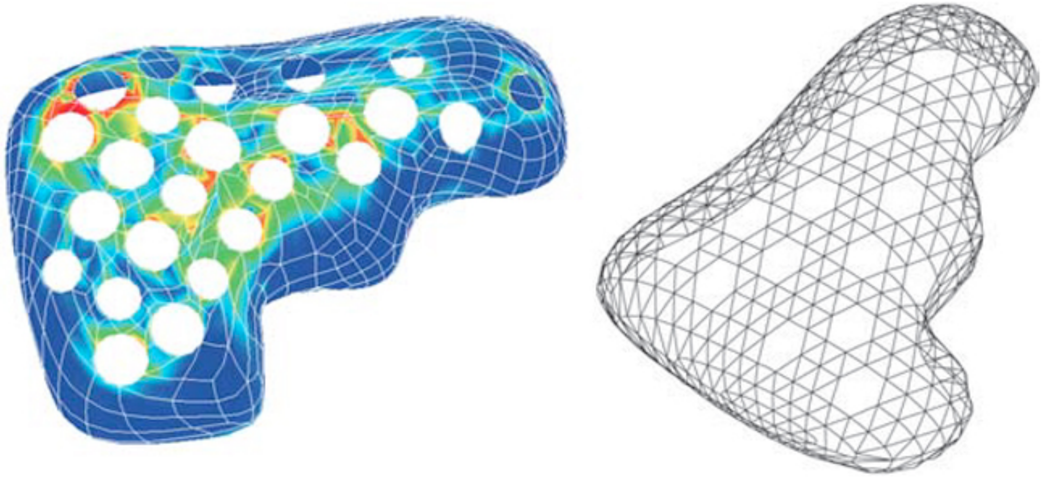
1.24 FEM analysis of structural frames in Dynaform, by : Harald Kloft. In : Performative Architecture

Because the structure was hidden in the space we have described before, the main job of the structural engineers rely in the geometric improvement, not with the intention of improving the geometric stiffness of the general shape but to design an outline of structural elements in the interstitial space and to adjust their organization so that they could work structurally stable.



1.25 Non structural Skin & Structural System in M.art.A. Museum, by : Harald Kloft.
In : Performative Architecture.

The internal and external surfaces purpose is to enclosure without any load-bearing distribution; their geometry outlined borderline boundaries that could not be altered. This project has a strong similarity with Franken's project, from which the surfaces acted as "master geometries" but these offered a small chance for modifying the structural behavior. In the Dynaform project, the layering was proposing a clear concept from which they could decide either if the structure was an inside or outside layer, or in-between. On the other hand, in Gherys project this functioned only in one feature as a technical necessity in-between. Peter Cook and Colin Fournier took an opposing approach with respect from Gehry, Cook and Fournier generated the digital model of the geometry for the Kunsthaus Graz in the moment they were developing the design, by transforming the conceptual competition idea into a digital environment. Although the idea was to continue as close as possible to the original form, Cook and Fournier did not follow this in an inflexible manner. Furthermore, the structural performance was approved to have an effect on the final geometry. For projecting the multifaceted roof of the Kunsthaus Graz, the principle assignment was to design a scheme of tubular steel elements that would resist an outer layer of acrylic glass panels with sophisticated forms. The external skin is formed by a sequence of disconnected layers, every one answering to a precise set of functional requests. For the structural layering,the team was searching to enhanced the stiffness and improved the structural system, so the best option relied in members that were going to be arranged in a triangulated pattern that worked as a hybrid structural system joining behavior of shell structures and bending systems .

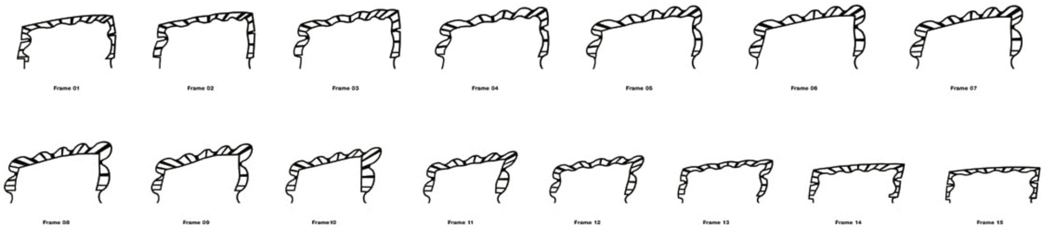


1.26 The finite element analysis of the complexly shaped skin for Kunsthaus Graz project, by : Bollinger & Grohmann. In : Digital Morpho genesis.

MANUFACTURING PROCESS

Constructing free forms have represented a problem around several matters, such as the absence of appropriate materials and production procedures that can be implemented in buildings with such qualities. What's more, most of building regulations do not contemplate new techniques and materials, incrementing the difficulty of constructing a complex shape. Normally this kind of buildings are archetypes, meaning that we cannot apply industrial processes that are suitable for the production of elements with complex shapes unless we require a large quantities for them to become economical. We are going to take as a reference the Dynaform project to understand the manufacturing processes involved in non standard forms. In Dynaform after evalueting different options, architects and engineers took the decision to detached the primary loadbearing structure from the structural secondary skin and to design a successions of primary steel frames. The architectural team produced fifteen cross-sections as "derivatives of the master geometry," each one of them was located at a different angle, consequently they were not parallel between each other and each one resulted in an exclusive shape. The next step they did was to inscribe the structural frames into the created cross sections.

They defined the outer outline of these frames as the offset from the "master geometry" surface, whereas the internal outline exemplifies a reversal of the same master form. The system was planned to work as a Vierendeel one, therefore, both outlines are joined at regular gaps with soldered plates in order to work structurally. The plates insinuate the origin of form generation; in this case is the virtual curvilinear route formed by a bmw car passing across the space from a distant point of view it seems the design of the Dynaframes appear to be distant from structural principles and strange looking, but they were generated under the global concept of form-finding principles described before.



1.27 Master geometry for the frames in Dynaform, by : Bernhard Franken. In : http://www.franken-architekten.de

Consequently, it was not created under a structural logic, the manufacturing process of the steel frames were cut from flat steel plates, then bent into figure and manually soldered together, the company on charge of elaborating this frames, had to take special attention to preserve tight tolerances on the digital 3D input data into a built shape. Before building the pavilion, they constructed a section of it containing numerous structural frames ; it allowed the architectural team to calculate the necessary assembly time and procedures aside from finding and solving troubles with the connections between certain elements. The exterior part of the pavilion is aimed to be the cleanest conceivable illustration of the "master geometry." An important issue was to elucidate a way of creating a skin that would make a smooth surface above the complex form.

About the materiality, an investigation was done to a number of different materials, concluding that the best option was a monoaxial pretensioned PVC membrane. The material was an accurate option due to the membrane could be pre-stressed among the structural frames and external folds in the skin were eluded. This envelope was tried on the real scale section of the pavilion, proving its behavior, the novelty of the material in architectural field, led to specialist mountain-climbing skills to assemble this membrane layer. The assembly of the pavilion was done with two months of anticipation, the methodology relied on covering with a membrane segment each span between neighboring steel frames The joints among membranes were closed with an apron fabric this decision was one of the few compromises, in order to maintain the general form, due to the short amount of time and the necessity for a waterproof envelope. The final design of the project was at the end clean, with materials and forms that were connecting with extremely ease. This project is considered to require more time, energy and creativity than a regular structure, the architectural and engineer group where coherent with the design line from the beginning, therefore; budget, deadlines and design intentions were not compromised. The Dynaform pavilion was in the same place for the period of time of the motor show; it was then disassembled and saved for future use.

To conclude, to shift into a design that is non-standard from architectural language point of view, requires novel manners of thinking from all sectors involve in the design process. It is indispensible that architects and engineers cooperate from the starting point of a project. Particularly speaking of non-standard or "freeform" architecture, a vital property of this collaboration is that the structural engineer has to understand the language of the architect and completely sustain the specific design approach. Appreciating individual capabilities will transform the cooperative discussion between engineers and architects. The analyzed projects sign the foundation of new prospects in construction. Complex curved shapes, comparable to the Dynaform and the Kunsthaus Graz project, were considered for a long time as unrealizable.

These projects are radical in the sense that all contributors involved: clients, planning parties and contracted firms understood the idea of working for a visionary architecture and accepted the probability of failing. In this framework, the way Franken's studio approached the parameter-driven design method in the Dynaform project was extremely helpful because that guiding line did not allow for geometrical alterations to the architectural model.

After considering and analyzing the different designing processes in non-standard architectures, some rules began to shape the work of engineers and architects methodologies; First, real scale sections models of the geometrically most complicated parts in the project are completely indispensable. This respond to the fact that issues that can't be solved in this real scale sections of the model are consequently not going to be solved in the real construction site either. Second, the digital model of the geometry that is going to be manipulated in manufacturing and construction must be completely parametric so as to simplify the fast production of the required data groups. For the Dynaform project, the consultants in charge of designing the structural membranes established a scheme for producing a ruled surface from the given geometry by dividing the membrane into parts which connect impeccably the cross-sectional frames in regions of analogous curvatures; that is the causal of why they could employ the uni-axial tensioned membrane without getting wrinkles on the surface.

Third, the regulation of layering throughout the manufacturing process must not be in charge of the construction corporation. This is an essential assignment in the digital workflow and it must be compulsive to be done by the design team, both by architects and by engineers. As an assignment, we can compare the layer control to the position of a compiler in a computer, it creates the specified code, with the data required for the execution. Lets continue talking about Dynaform project, the 3D model of the geometry produced in the architectural form generation process consists of one-layer that comprises of surfaces without material definition as well as without thickness. At the final instances of the design, a cohesive multilayered 3D model is manufactured; this one incorporates all the information necessary for building it up. During the building process, however, that 3D model suffers several variations depending on the tolerances and precise requests of production. The assignment of surface control is to deliver to every manufacturer with a precise layer of information that is required.

To sum up, the emerging digital design and production environment, joint with new materials and contemporary technologies, gives exceptional opportunities for architecture that attempts to perform entirely in a technical, financial, conceptual, formal and material sense. Under that environment, structural engineers can exploit the inventive power of the discipline, not only by accompanying the architects with the computations, but by comprising their ideas and comprehending the digital form generation opportunities structurally and materially. The non-standard, freeform, and performative architectures suggest a promise of new collective design synergies for architects and engineers.

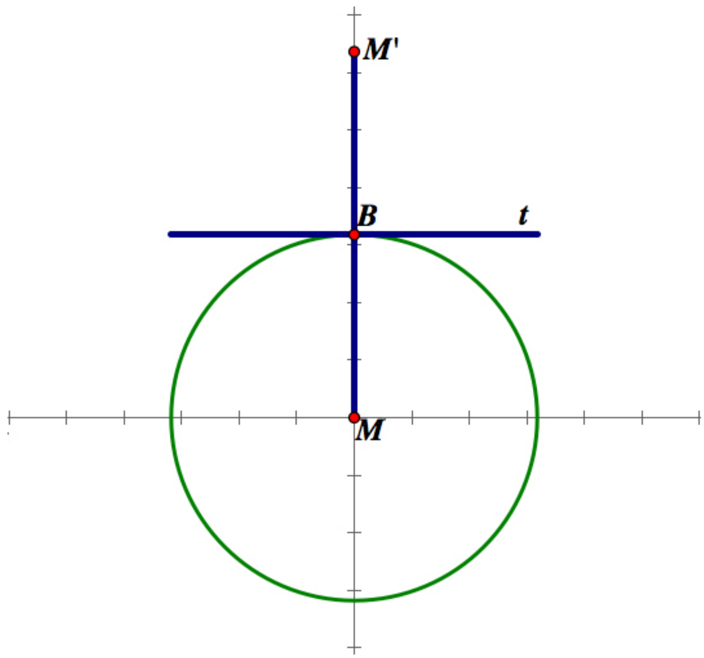
Images

Chapter Two

Geometrical Elements

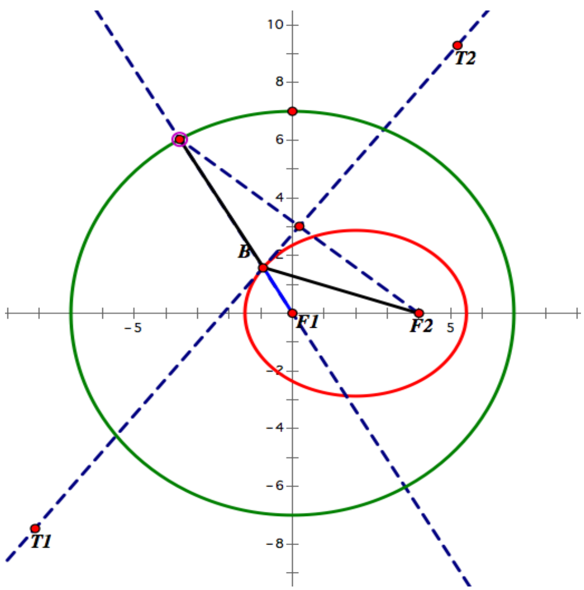
Simplest curves and surfaces

The simplest surface is a plane, the simplest plane curve is a line, which is the shortest connection between 2 points. A simple curve as the circle has led us to several investigations, a circle is defined as a curve whose points are at a constant distance from a given a point. A compass or a threat does its construction, for this reason is considered a convex or closed curve. In this figure a tangent line can be drawn in any part of it (Graph 2.1).. If B is the point of contact, MB is the shortest segment joining the center M to the tangent T. not for the others *t.* MB is perpendicular to the tangent, we prove this reflecting M on the tangent line M'⇒⇒MB is the shortest path from *t,* then by symmetry M'B is the shortest length from M' to *t,* the segment MBM' is the shortest form M to M' thus is not bent at B⇒⇒MB is perpendicular to *t.*

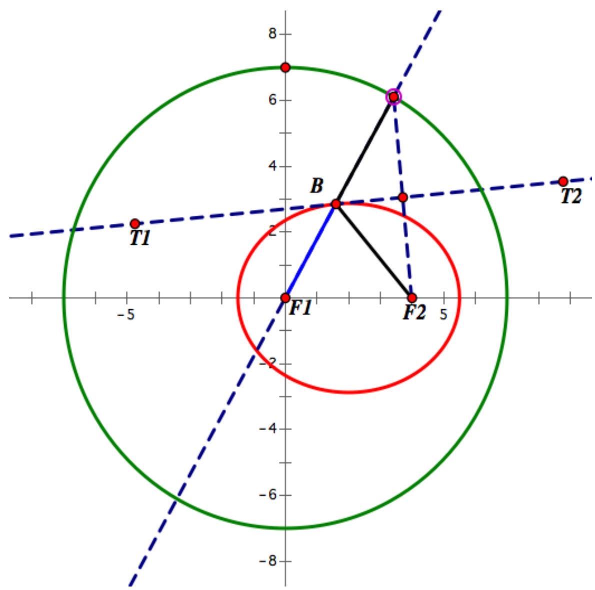


Graph 2.1 Simple Curve : Circle

Constructing a circle with a thread implies to hook a fixed point (center) and keep the thread stretched while drawing the circle. The ellipse is construct in a similar way, but using two fixed points named *foci.* The sum of the distances from 2 given points to any point of the curve (ellipse) is constant. If this distance is diminished, we obtain again the circle (Graph 2.2). As the circle the ellipse has a tangent line in each point of the curve. The focal *radii* are two line segments connecting a point of the ellipse with the *foci.* Like in the circle every tangent to the circle is perpendicular to the radius, in the ellipse every tangent forms equal angles with the focal *radii* at the point of contact; $< F_1BT_1 =< F_2BT_2 < F_1BT_1 =< F_2BT_2$. To prove this fact we reflect F_2F_2 in the tangent $F_2'F_2'$ the straight line $F_1F_2'F_1F_2'$ is the shortest segment joining F_1 and F_2',F_1 and F_2', they intersect with B_1B_1; $F_1B_1F_2$ $F_1B_1F_2$ is the shortest path from F_1F_1 to F_2F_2 via the tangent. As B_2B_2 is any other point in the tangent; $F_1B_1F_2 = F_1B_1F_2{'}F_1B_1F_2 = F_1B_1F_2{'}$, is longer than $F_1B_1F_2 = F_1B_1F_2{'}F_1B_1F_2 = F_1B_1F_2{'}$, but shorter path from F_1F_1 to F_2. F_2. Then, F_1F_1 and F_2F_2 are symmetrical with the straight line $T_1T_2T_1T_2$; $< F_2B_1T_2 =< F_2B_1T_2$ $< F_2B_1T_2 =< F_2B_1T_2$ as well $F'_2B_1T_2 = F_1B_1T_1F'_2B_1T_2 = F_1B_1T_1$ in the vertical angles. As the construction of the ellipse, the hyperbola shares the same notion, the principle rely on the fact that the difference of the distances form two fixed points to any point in the curve is constant. The parabola can be obtained from the ellipse by a limiting process, in this way we fix F_1F_1: the focus and S the vertex which is near to this focus.



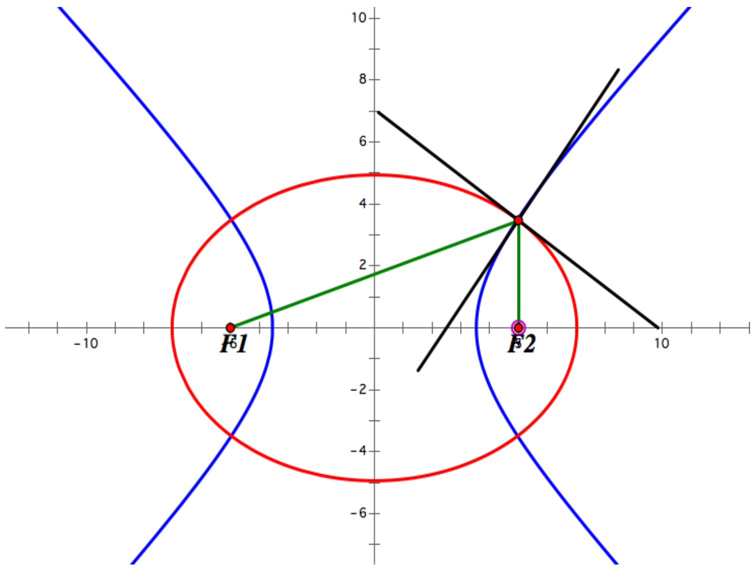
Graph 2.2 Ellipse Generation



Graph 2.3 Ellipse Generation

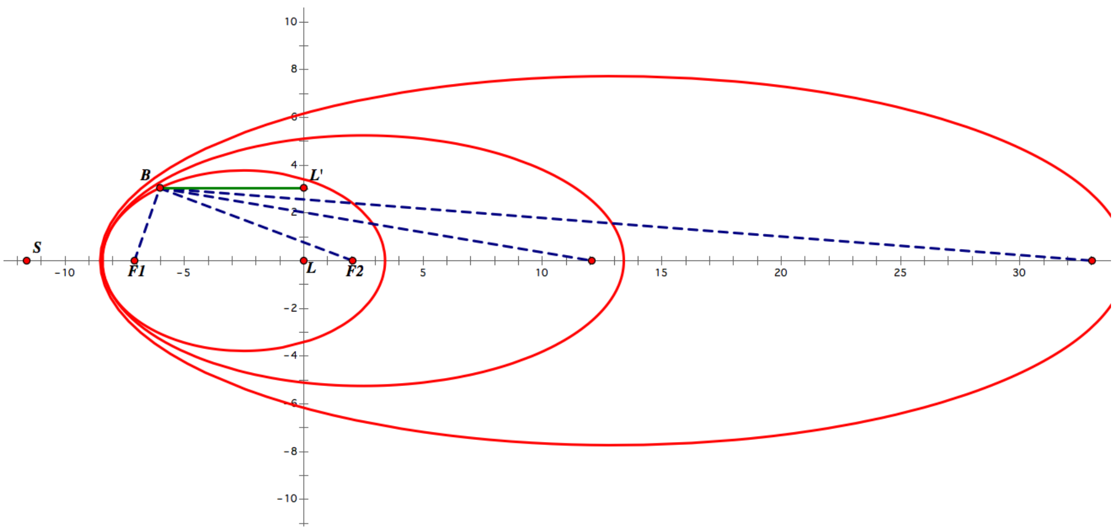
If we consider the second focus F_2F_2 to continue its path under the line SF_1SF_1 going further away from F_1F_1, it reaches a limiting curve and then we arrive to the parabola. The definition is like this; in the thread construction the distance between $F_1F_2F_1F_2$ is large enough, therefore F_2F_2 is nearly parallel to SF_1F_1 as long as we are drawing it near

S(Graph 2.3). Then a perpendicular $\ell\ell$ is drawn at any point L on $F_1F_2F_1F_2$ and if L' is the foot of the perpendicular made from B on to $\ell.\ell$. $F_1B + BF_2 = F_1B + BL' + LF_2 = const$ $F_1B + BF_2 = F_1B + BL' + LF_2 = const$. Meaning that a parabola is a curve in which the sum of the distances of any point on it from a fixed point and a fixed straight line is a constant. Now lets take in consideration the family of hyperbolas that have the same pair of *foci* as the ellipses, there are exactly two curves of the system of confocal ellipses and hyperbolas passing through every point of the plane (Graph 2.4).

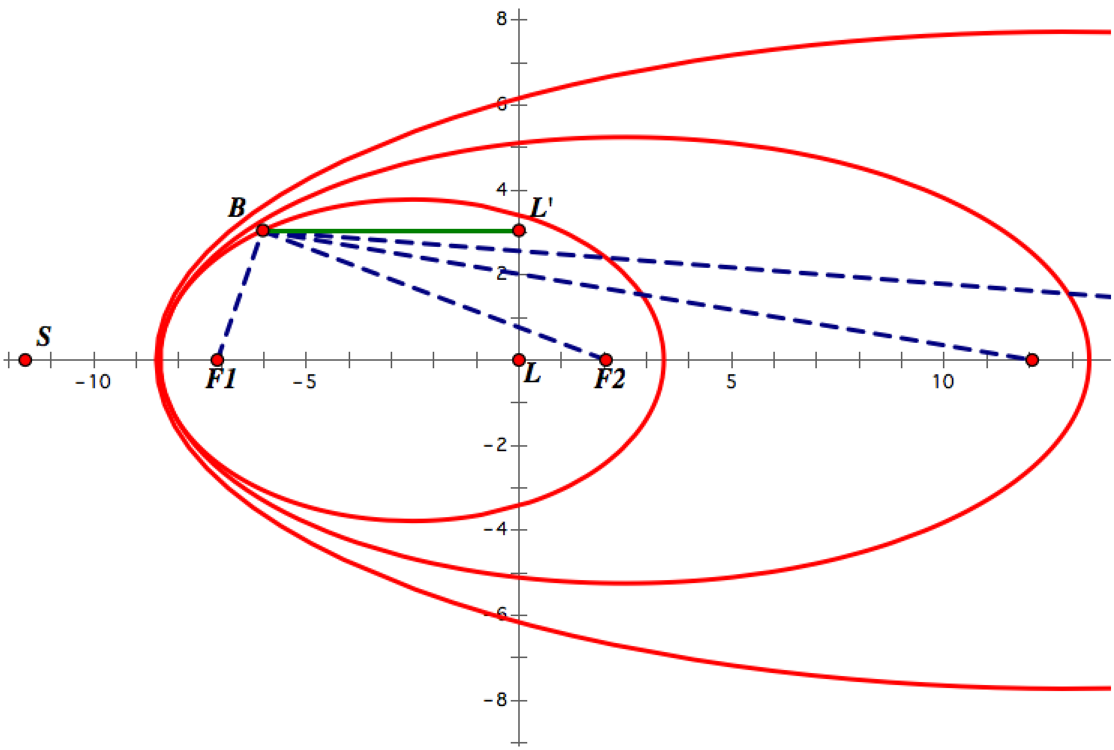


Graph 2.4 Construction of Hyperbola from ellipse

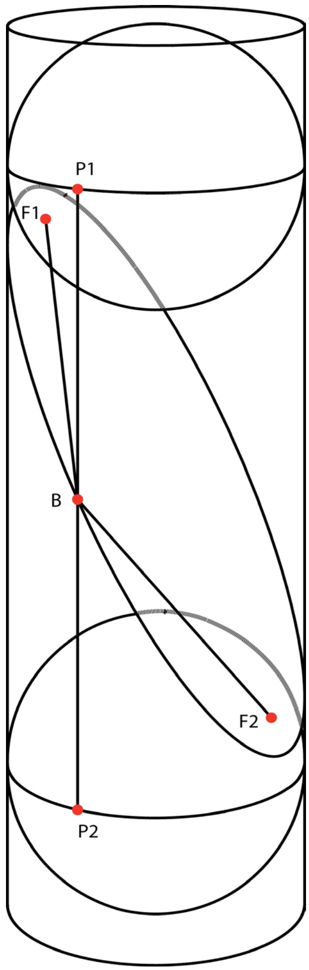
The confocal hyperbolas and ellipses make a net of curves or orthogonal net of curves. They are called orthogonal due to the each curve family intersects themselves in right angles, where the angle in the moment of the intersection of these two curves are the tangents in this point. To obtain an overall view of the system of curves we should start with the bisector of $F_1F_2F_1F_2$, which at the beginning exposes flat ellipses, that gradually become circles as they grow .



Graph 2.5 Construction Relation between Ellipse and Hyperbolas



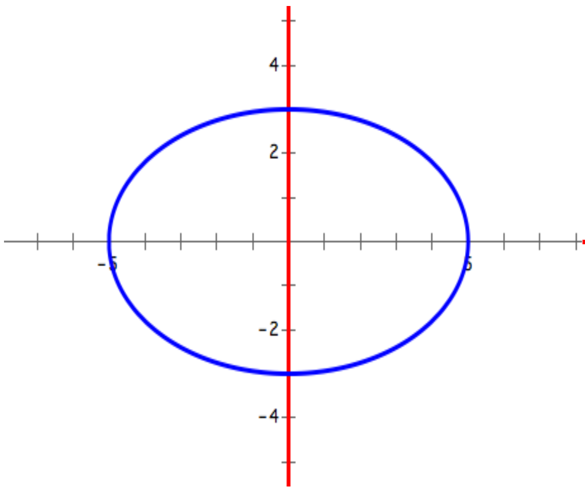
Graph 2.6 Contruction Points for the Ellipse and the Hyperbola



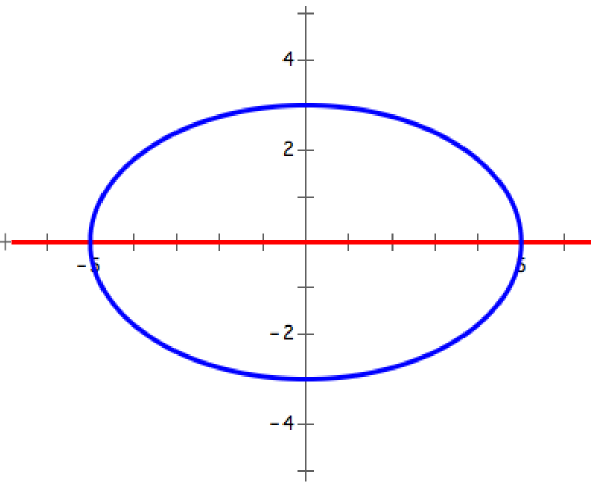
Graph 2.7 Construction of the Circular Cone

The cylinder

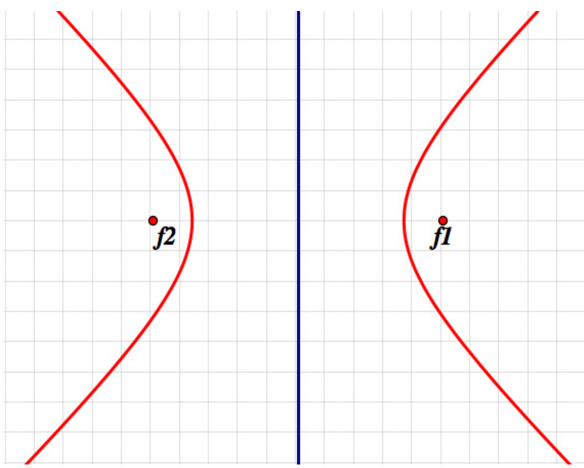
As the circle was the simplest curve, the circular cylinder is the simplest surface. Its construction relies on the simplest curves as the straight line and the circle; the straight line is moved around the circumference of a circle keeping it perpendicular to the plane of the circle, the circular cylinder becomes a surface of revolution. These kind of surfaces are characterized by the property that they can be generated by the rotation of a plane curve about an axis. In the case of a circular cylinder every plane intersects it in right angles to its axis in a circle, a plane that is neither parallel to the to the axis or at right angles; intersects the cylinder in a curve; actually an ellipse. In order to prove this we proceed in this way: we take 2 spheres that intersect the planes, they are touching the cylinder in two circles and the intersecting plane at two points $\mathbf{F}_1\mathbf{F}_1$ and $\mathbf{F}_2\mathbf{F}_2$, *B* is any point of the intersection curve of the plane with the cylinder, this is a parallel straight line to the axis that lies on the cylinder. This line meets the circles of the spheres in two points P_1P_1 and P_2P_2 from point *B,* BF_1F_1 and BP_1P_1 are tangents to the sphere. These tangents should be equal due to the property of the sphere of rotational symmetry. $BF_1 = BP_1F_1 = BP_1$, similarly $BF_2 = BP_2F_2 = BP_2$; $BF_1 + BF_2 = BP_1 + BP_2 = P_1P_2$. $F_1 + BF_2 = BP_1 + BP_2 = P_1P_2$. As the distance $P_1P_2P_1P_2$ becomes independent of the point *B* on the curve, because the rotational symmetry of the sphere, Thus $BF_1 + BF_2F_1 + BF_2$ is constant for all points *B.* Accordingly, the ellipse appears with its *foci* at F_1F_1 and F_2F_2.



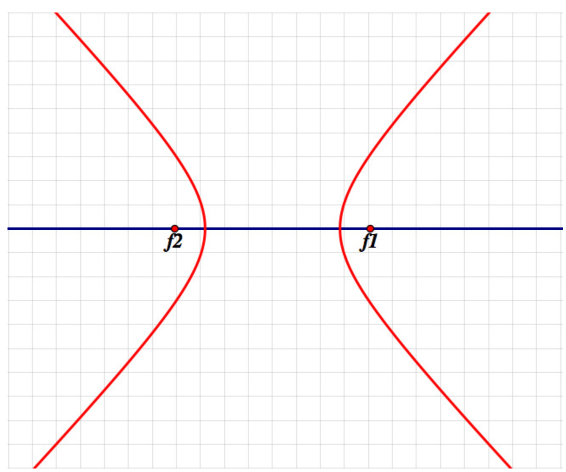
Graph 2.8 First axis of Symmetry in the ellipse



Graph 2.9 Second axis of Symmetry in the ellipse



Graph 2.10 First axis of Symmetry for the Hyperbola

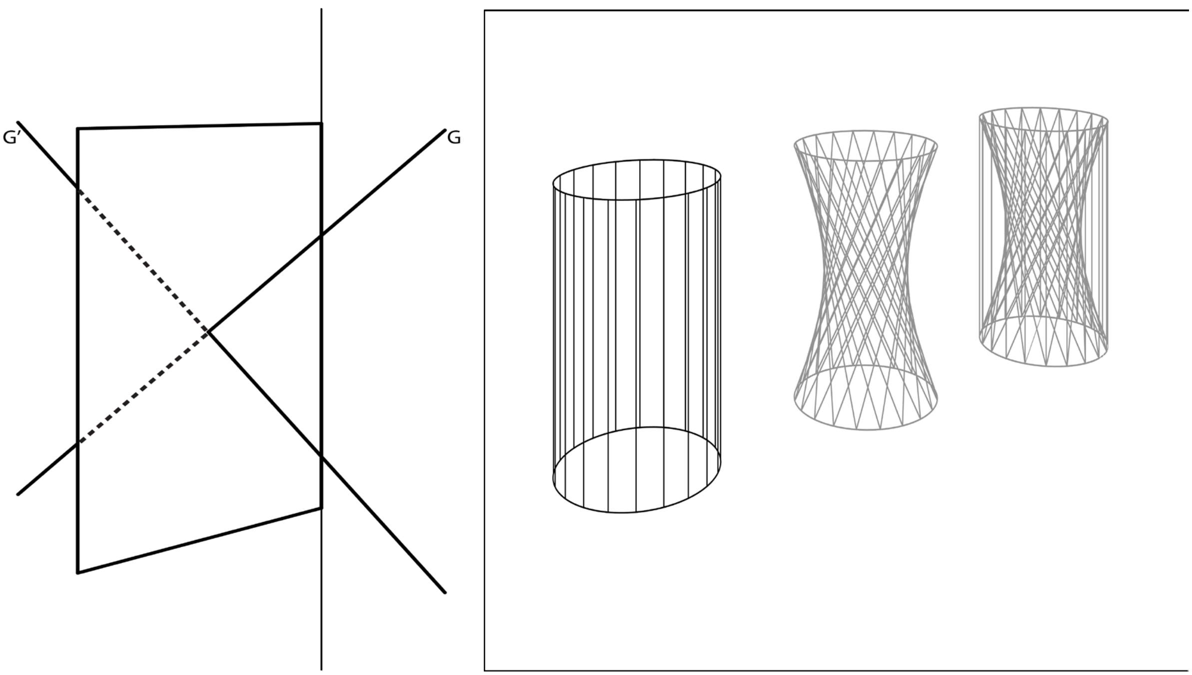


Graph 2.11 Second axis of Symmetry for the Hyperbola

Circular Cone

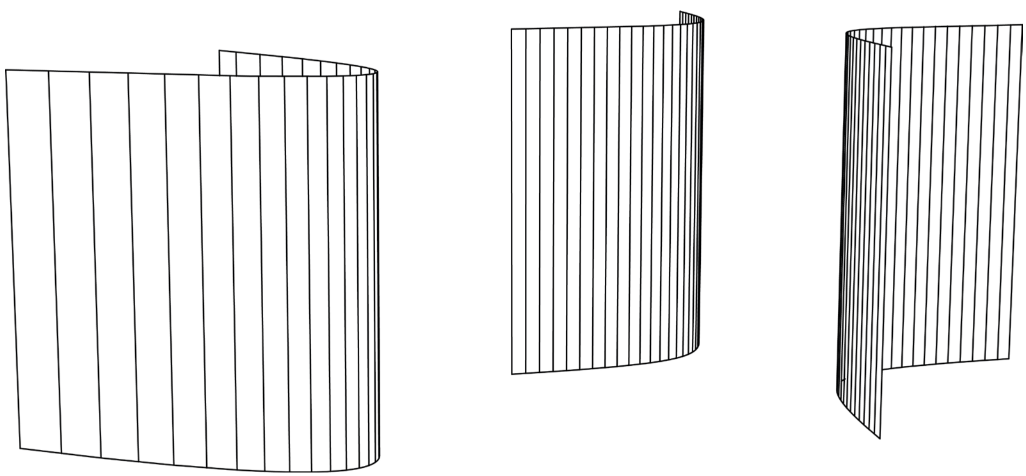
The next surface of revolution is the circular cone, its construction starts by rotating a straight line about an axis that intersects it. If we draw a plane that is perpendicularly to the axis of the cone it will intersect it in a circle. Like in the previous example if we inclined this plane the result section will be an ellipse. If this plane continues to incline towards the axis of the cone; the ellipse becomes more elongated up to being parallel to the generating line of the cone, as we did before, the section becomes a parabola. Now if the intersecting plane is still near the axis of the cone meeting the both branches of it. Is noticeable to elucidate a hyperbola. In order to prove this, we take into consideration the two spheres in each branch of the cone touching both the cone and the intersecting plane. So $BF_1 = F_1 = BP_1BP_1$, $BF_2 = F_2 = BP_2BP_2$, $BF_2 - BF_1 = BP_2 - BP_1 = P_1P_2 = const$
$F_2 - BF_1 = BP_2 - BP_1 = P_1P_2 = const$.

We have noticed that each plane that has intersected the cone without taking into account its vertex had as a result a ellipse, parabola or hyperbola, the relation between these curves define them as conic sections. During this process in which the intersecting plane encounters the vertex or the cone degenerates in a cylinder, other types of configurations arise. For example; a single point, a straight line-counted twice-, two intersecting straight lines, two parallel straight lines, and the empty plane these are considered as degenerate conics.



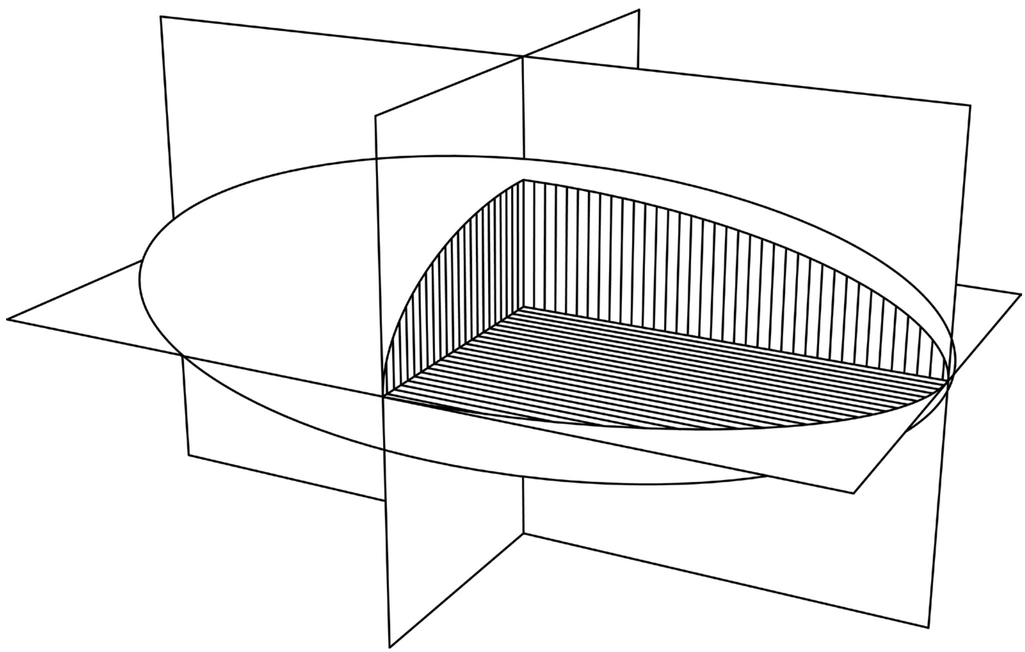
Graph 2.12 Symmetry and revolution from the hyperbola

Now lets take a look in consideration surfaces of revolution of conic section, for doing this we should establish the axis of rotation as the axis of symmetry. For instance; the ellipse has 2 axis of symmetry, as a result, 2 different surfaces; a Prolate spheroid and a Oblate spheroid(Graph 2.5 & 2.6). The parabola gives rise to the paraboloid of revolution, because of its only one axis of symmetry (Graph 2.7). The hyperbola has the quality of giving two diferent surfaces of revolution, the *hyperboloid of revolution* of two and one sheets,(Graph 2.8 & 2.9) it has one particularity, the surface can also be generated by rotating a straight line about a skew axis. We can proceed to proof this in a visual way. Let we have two symmetrical lines named *g* and *g'* with respect to a plane through the axis *a* (Graph 2.10). Therefore *g'* must generate by rotation the same surface as *g.* Hence, two families of straight lines appear on the hyperboloid of revolution of one sheet, covering completely the surface, the 2 families of straight lines intersect each other.(Graph 2.11)



Graph 2.13 Procedures to arrive to a elliptical cylinder.

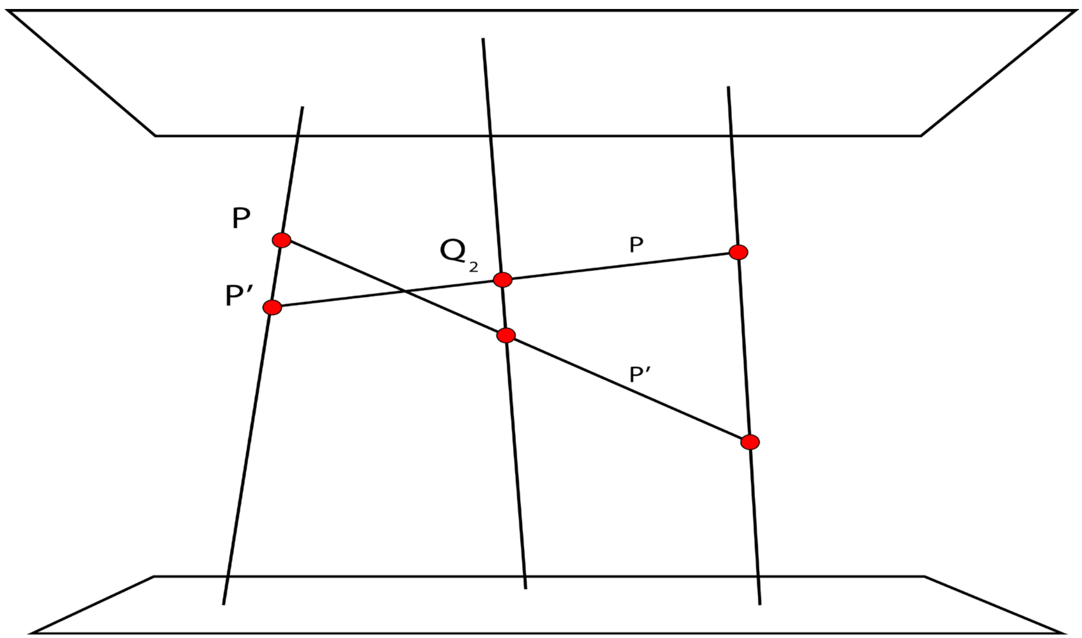
Lets take a look into study of the space through systems of discrete elements. Pane Lattices; the simplest system of discrete parts is the square lattice in the plane . Its construction process starts by marking the four corners of a unit square in a plane, then we move 1 unit of length in a parallel direction, to one of its sides and mark the two new points, we repeat the same process in the other direction indefinitely, the 2 resultant stripe rows are moved 1 unit length perpendicular to themselves, repeating the process indefinitely and marking the new points. In this manner, we constitute the square lattice, from this lattice construction we cannot only arrive to square figures, but also to parallelograms that maintain the same area as the generating square. In order to determine the upper bound of these lattices we should proceed, as we know *C* becomes the minimum distance between a pair of pair of lattice points. (Graph 2.12). The straight line *G,* contains a not defined number of lattice points at intervals of length *C,* just as the other stripe *h* is at 1/c and is parallel to *G.* we proceed to draw a number of circles of radius *C* on the straight line *G.* These circles are covering a strip of the plane bounded by circular arcs. By definition of *C,* every interior point of this strip is less than *C* distant from at least one lattice point, therefore the interior point cant be itself a lattice point. Consequently, 1/*c* is greater than or equal to the shortest distance between the boundary of the street and *g.* in this way we find out that this distance is the altitude of an equilateral triangle $\frac{1}{c} \geq \frac{c}{2}\sqrt{3}, c \leq \sqrt{2}/\sqrt{3}\frac{1}{c} \geq \frac{c}{2}\sqrt{3}, c \leq \sqrt{2}/\sqrt{3}$: this is the desired upper bound for *C.*



Graph 2.14 Deformed Spheroid

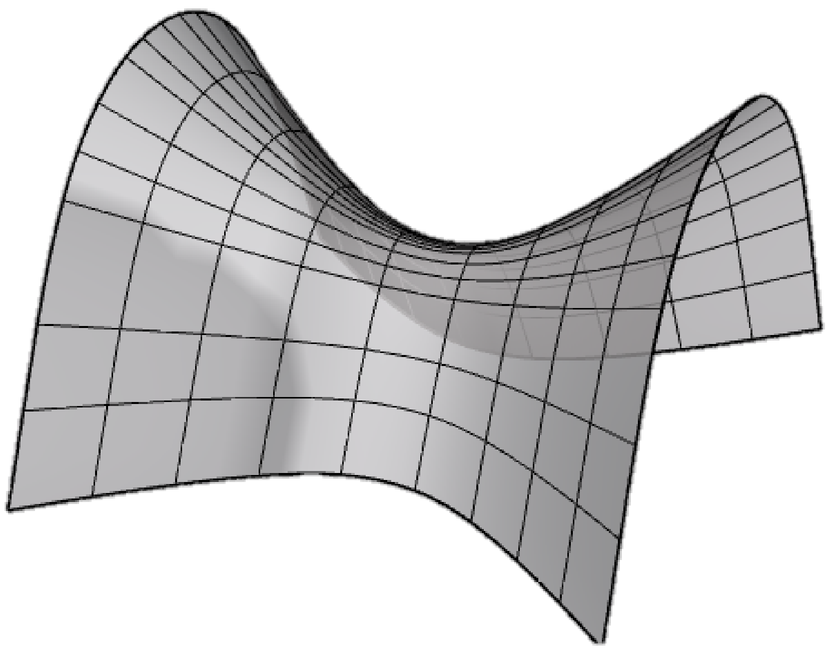
The second order surfaces

These types of surfaces are obtained by rotating conics, they are also called quadrics, due to they satisfy equations of the second degree in a three dimensional Cartesian coordinates. Lets have a look into the different types of quadratics; to obtain an elliptic cylinder a straight line is moved along an ellipse so this line is always perpendicular to the plane of the curve. If we apply the same procedure to a parabola and a hyperbola, we will get as a result their cylinders. What's more, in order to get elliptical or cone cylinders, we can obtain them from the corresponding surfaces of revolution by a process of deformation called *dilatation,* we proceed to hold fix all the points of an arbitrary plane that contains the axis of rotation and continues to move all the other points in a fixed direction away or towards the plane, so the distances from the plane of all points in space change in a fix ratio.



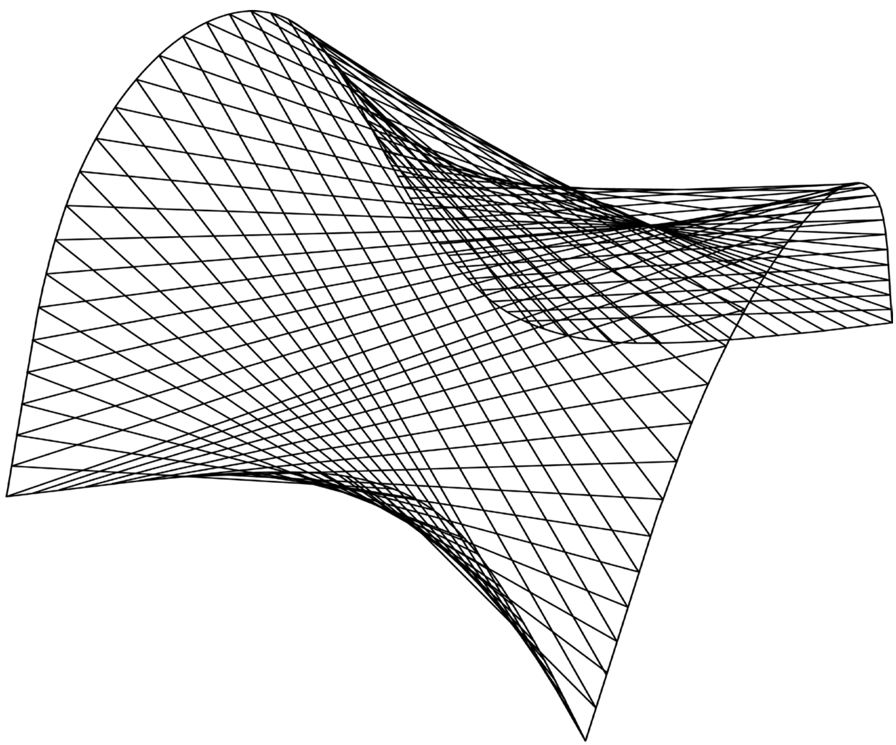
Graph 2.15 Hyperboloid of Revolution construction.

By applying these kinds of transformations, it's correct to conclude that this methodology transform circles into ellipses (or circles), planes into planes, straight lines into straight lines and all the second order curves and surfaces into second order curves and surfaces respectively. As an example lets have a look to the spheroid by dilatation process we will get the most general ellipsoid. The spheroid is symmetrical about every plane through the axis, however the general ellipsoid has only three planes of symmetry. They are the general planes of the ellipsoid and are mutually perpendicular, by its construction we can infer that that their segments of their lines of intersection cut off by the surface are three unequal axes, named, the *major, mean* and *minor* axes of the ellipsoid (Graph 2.14).Therefore, if we would like to transform the general ellipsoid back into an oblate or a prolate spheroid we will have to use the dilatation process, so the *major* and *mean* or the *mean* and the *mino*r axis become equal. In the case of hyperboloid and paraboloid of revolution by dilatations, these are capable to produce the most general surfaces as the hyperbola of one or two sheets and the elliptic parabolloid, the hyperboloids have three principal planes and the elliptic paraboloid has two.



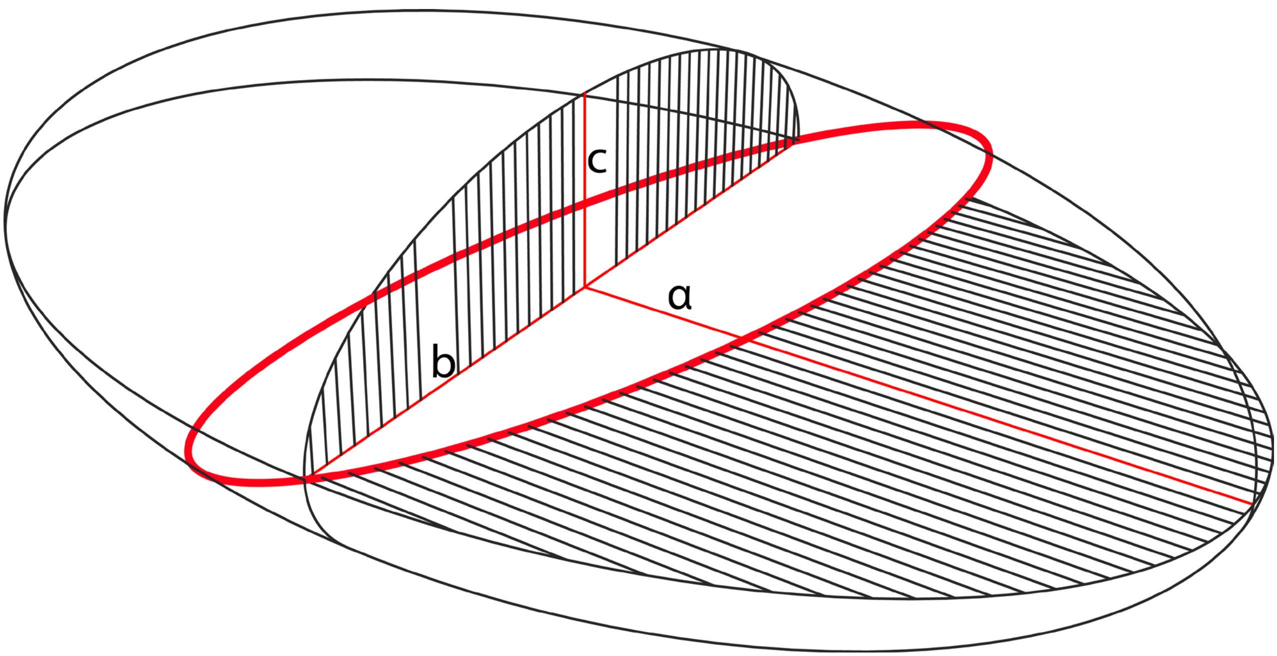
Graph 2.16 Saddle

Two families of straight lines form the general hyperboloid of one sheet. As mentioned before in the dilatation process straight lines will always transform into straight lines, Their arrangement is in such way that every line of each family has a point in common with every line of the other family and any two lines of the same family are skew. Lets proceed to the construction of this hyperboloid; we pick any three straight lines of one family, because isn't possible for two of them to have a plane in common, each point P is on one and only one straight line of P meting the other two given lines, to be more is the intersection of the plane containing P and the second line containing P and the third line. Even though, P has three points in common with the hyperboloid, no straight line can intersect a quadric in more than two points. Thus, P must be one of the lines of the hyperboloid. Now lets imagine point P traverses the first line, this corresponding line P will assume the positions of all straight lines of that family on the hyperboloid to which the first line doesn't belong. Consequently, if we pick any three straight lines of this family, we will discover the other family by using the same procedure, including the 3 lines from which we start originally. During the construction we found that every pair of straight lines that belong to the same family must be skew, it is possible then to find three non-coplanar straight lines in one of the families. For instance, lets say we could find three skew straight lines to do the construction, while *P* and *P'* were to meet at a point *Q*, (Graph 2.15), the original lines are forced to lie in the plane *PP'Q*, which is incongruous to one of the assumptions. Therefore, is clear that our surface is not going to be a hyperboloid, but a plane if the three lines of a plane turned out to be coplanar. Consequently, these three skew straight lines define a hyperboloid of one sheet, with an exception; when all lines are parallel to one plane (but not to each other). When the latter condition is fulfill a new type of second order surface appears, named the hyperbolic paraboloid and it doesn't include any surface of revolution as a special case.

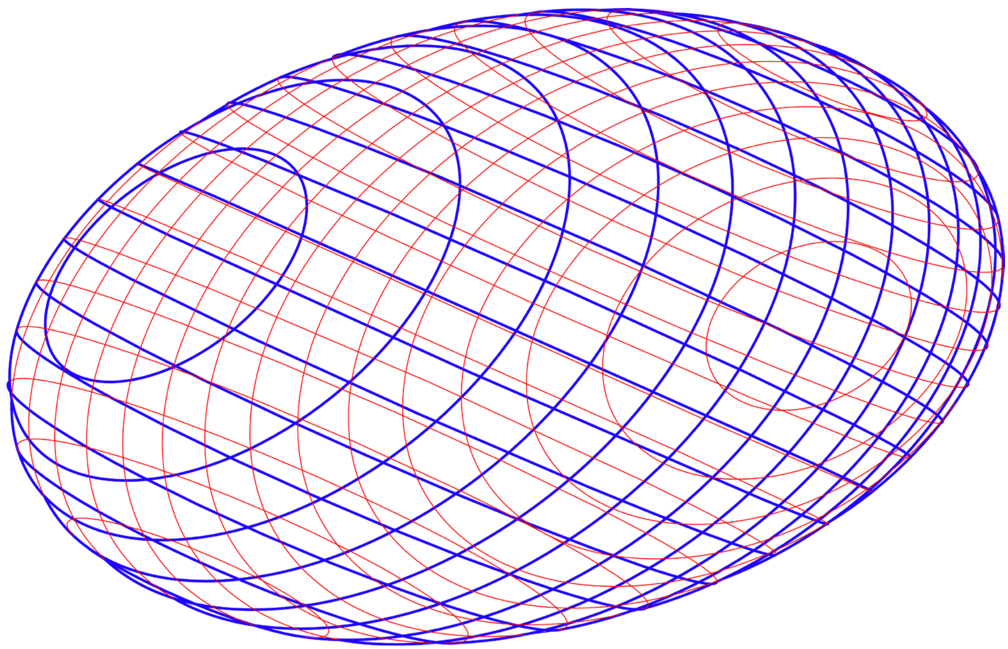


Graph 2.17 Straight lines in a saddle

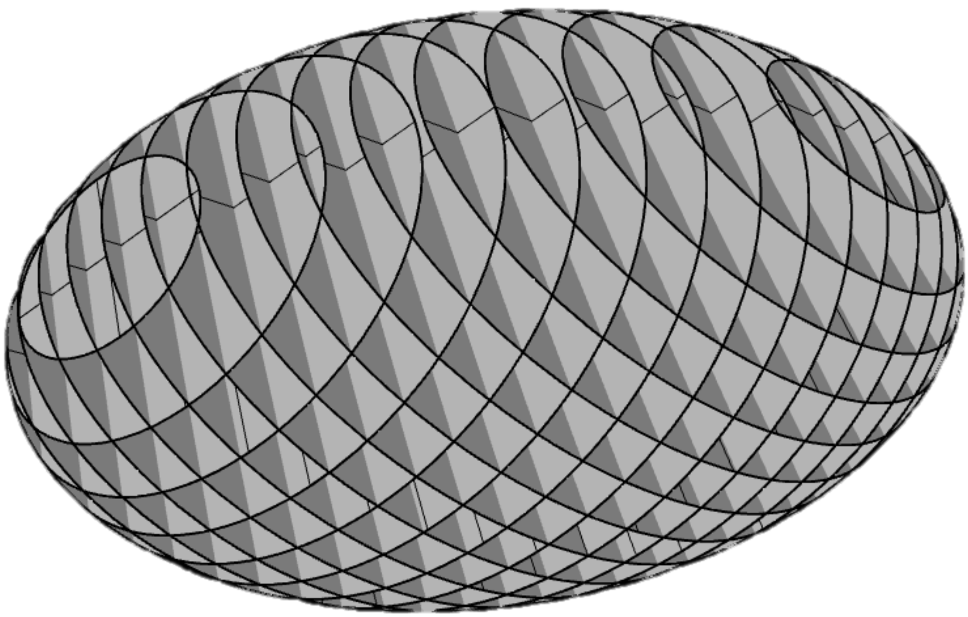
The hyperbolic paraboloid resembles a saddle (Graph 2.16), it has two equally perpendicular planes of symmetry that intersects in parabolas. As for generating the surface we needed three straight lines, laa straight lines that belonged to a given one of the two families are parallel to a fixed plane. If we have a closer look into how the planes intersect our surface in a curve that extents to infinity, we realize that its intersection cant be an ellipse. This fact helped us to realize that the hyperbolic paraboloid couldn't be obtained by any surface of revolution by a dilatation, in every surface of revolution circles are present and in this case the circles will be transformed in ellipses by a dilatation process. We have reached a point in which a new method for generating surfaces has been discerned, it mainly consists on fixing a certain path in space in which we move a straight line. The surfaces that are generated by this method are called *ruled surfaces.* To be more specific they consist of a conem the hyperboloid of one sheet, three kinds of cylinder and the hyperbolic paraboloid. The hyperbolic paraboloid and the hyperboloid of one sheet have a special property about each point of the surface is on more than one of the straight lines, these kind of surfaces that contains two families of straight lines or *rulings* is called a *doubly ruled surface.*



Graph 2.18 Inscribed Circle in an Ellipsoid



Graph 2.19 Ellipsoid Constructive Relations



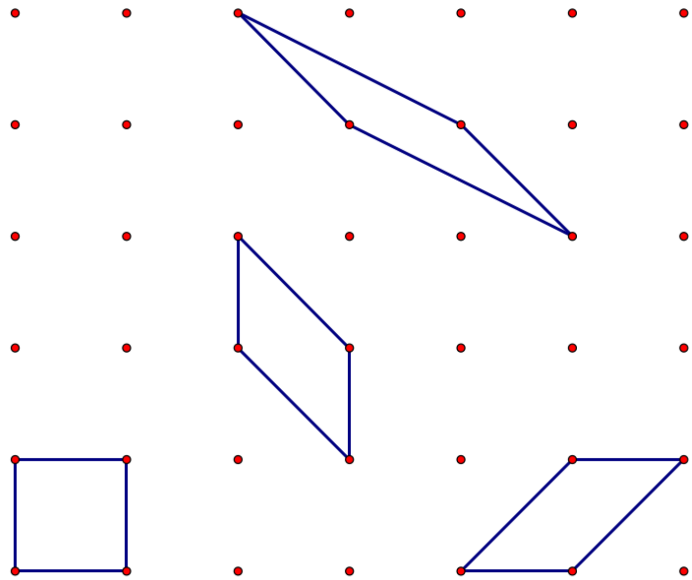
Graph 2.20 Sectioned Ellipsoid

The ellipsoid, the elliptic paraboloid and the hyperboloid of two sheets cant contain any straight lines, due to the fact that any of these surfaces could extent into infinity in any two opposite directions. Lets talk about the property of the two families of straight lines that lie on the hyperbolic paraboloid and the hyperboloid of one sheet, lets picture all these straight lines to be made of a rigid material and fixed together at all the crossings in a manner that permits rotating but not sliding. A first look to the framework of the fixed straight lines would seem rigid, however this framework is movable. To understand the way in which the model of the hyperboloid can change its form, we have to fix the principal plane in a horizontal position whose intersection with the surface is an ellipse and try to deform the framework in such way that this plane always continues to be a principal plane. Until this point we have found two doubly ruled surfaces; the hyperboloid and hyperbolic paraboloid (excluding the plane), we have conclude as well that the structure obtained by deforming the rod model of the hyperboloid can remain a hyperboloid or become a hyperbolic paraboloid, however in the latter case we can prove it can't occur. Next, lets try to elevate the framework up in a manner that we make the rods become more perpendicular to the principal plane, in such manner the surface will become progressively less curved. We will reach a point in which the principal plane traverses the group of confocal ellipses which progressively will become more narrow, until the limit, wherein the framework will fold into a vertical plane, the rods will become tangents at a hyperbola in this plane, on the other hand the horizontal ellipse will transform into a double straight-line segment.

There is another feature for classifying the quadrics that are divided in two categories. The first three are; the hyperbolic and parabolic cylinders and the hyperbolic paraboloid, these don't intersect any plane in a circle due to any plane section of any one of these surfaces extents to infinity. For the other six types of surfaces several circles are present, these notion is clearly linked to the fact that that these six surfaces include surfaces of revolution in contraposition of the first ones. Lets have a look to the ellipsoid to demonstrate a graphic prove of the existence of circular sections (Graph 2.18). Each plane through the mean axis *b* slices the ellipsoid in an ellipse having one axis equal to *b.* Starting with the plane comprehending *b* and the minor axis *c* of the ellipsoid and rotating about *b* until the plane containing *b* and the major axis a of the ellipsoid is gotten, the section is at first an ellipse with its other axis shorter than *b,* but in the final position is an ellipse with its other axis longer than *b.* Somewhere in between there is a position of the intersecting plane where the second axis is equal to *b,* so that the section is a circle. The inherent property of symmetry of the ellipsoid leads to a second plane through *b,* that is obtained by reflection of the first one in the plane (*b,c*), this intersection with the surface produces as well a circle. What's more, we can prove that every plane that is parallel to a circular section is also intersecting the ellipsoid in a circle. Consequently two families of parallel circles appear on every ellipsoid, as for the ellipsoid of coincide.

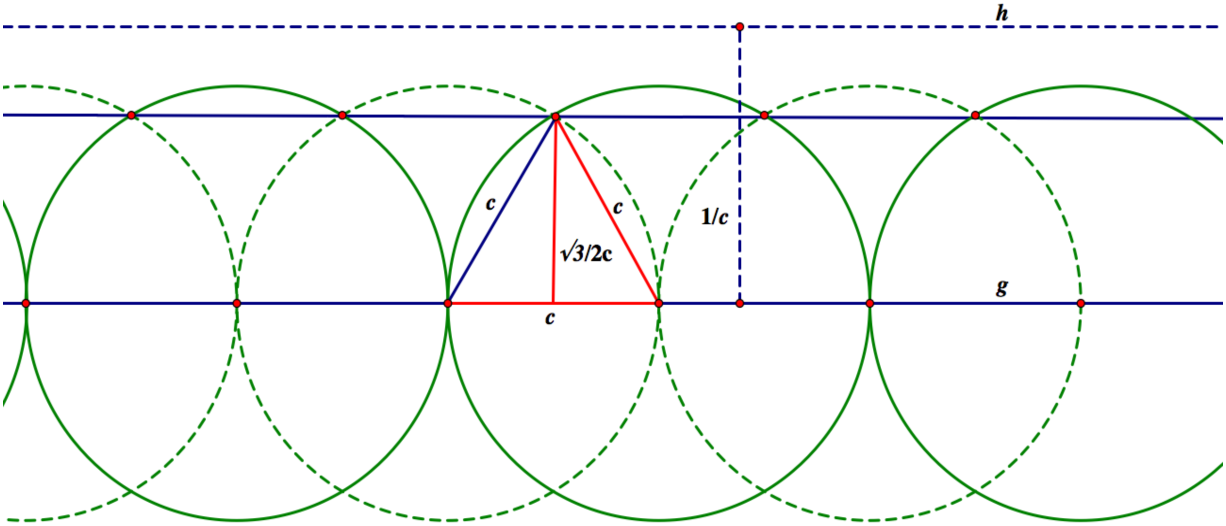
A new theorem appears in the dissertation, its related with the one considered for the straight lines on the hyperboloid, in this case we apply it to the two families of circular sections. Lets picture that all circles are attached together at their points of intersection, so in this way they are able to produce a rotation, but not to slide. Lets have a look to the resultant framework (Graph 2.19&20), in this case the framework is not rigid, but movable. In the image we can see how the circular disks are joined in the area of intersections, if we proceed to change the form of the moveable models of circular disks we will get certain families of surfaces that are not exactly the ones we get by using the rod models. For instance, this model of circular disks that form a general ellipsoid could transform into the form of a sphere, in this case every section by a plane of symmetry is a circle, even though in the construction of confocal ellipses a circle cannot appear. For example, like in the rod model, if we continue to move the model of circles to such an extent, it will fold up into a plane. While the two models present strong differences they are correlated by a transitional case. In the case of the moveable rod model of the hyperbolic paraboloid, is clear to perceive it as a limiting case of a circle model in which the radii of the circles become infinite when the circles transform in straight lines. In the case of having a family of hyperboloids of one sheet that is reaching the form of a hyperbolic paraboloid , we will see how the circles and the straight lines are on the hyperboloid become straight lines in the paraboloid.

Lattices in 3 and more than 3 dimensions

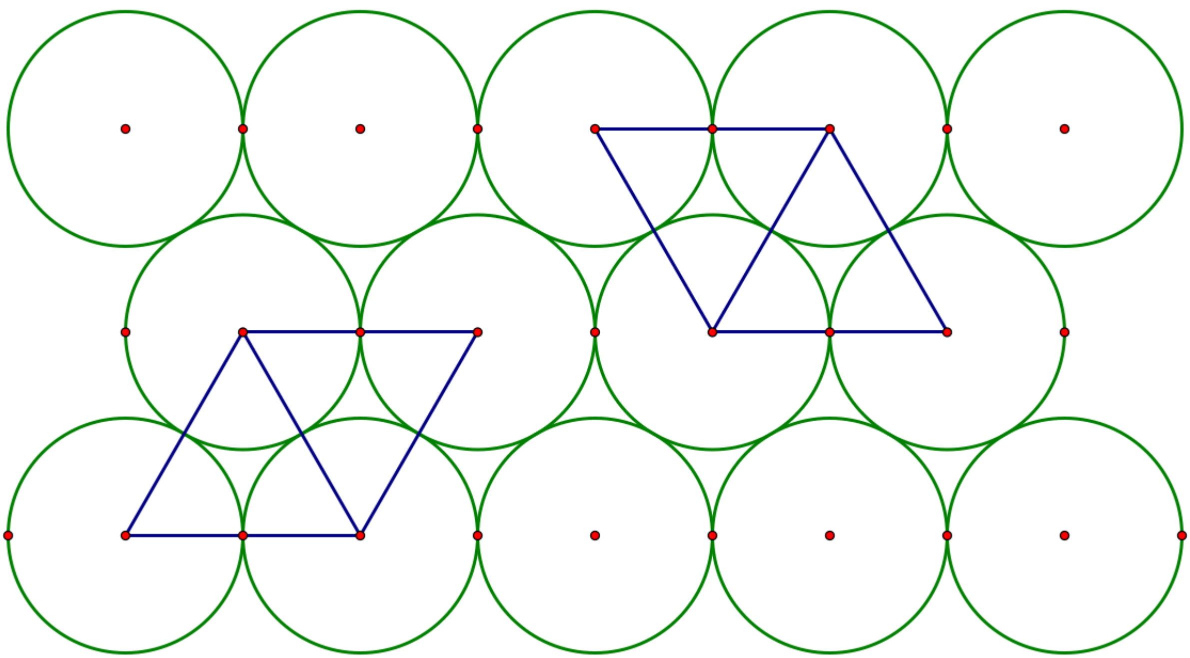


Graph 2.21 2D Lattice

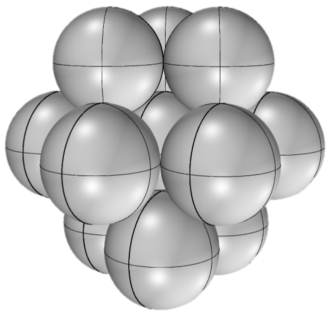
The space lattice is constructed from a parallelepiped, using in the 3d space a similar process as the one used in the two dimensions from a parallelogram. The 3d lattice can be generated by parallelepiped of different forms keeping their same volume and having its corners at points of the lattice and not at its interior or on its surface. As we ured out in the plane, the space lattice doesn't have a lower bound, but an upper one. To accomplish this we use the same method as in the plane, but instead of an equilateral triangle, we employ a regular tetrahedron and instead of using two equilateral triangles for generating a parallelogram, the regular rhombohedron is used in space. The result volume of this parallelepiped is $c^3/\sqrt{2}c^3/\sqrt{2}$, in this case *C* is the length of an edge of the tetrahedron; its volume has to be equivalent to a unity then $\frac{c^3}{\sqrt{2}} = 1\frac{c^3}{\sqrt{2}} = 1$ or $c = \sqrt[3]{\sqrt{2}} = \sqrt[3]{\sqrt{2}}$. The result leads us to find the best solution for packing the spheres in the closest way; the centers of the spheres form the rhombohedron lattice, therefore when the sphere has a unit of radius, the length of the edges of the tetrahedral is two, in this way the volume unit is expressed as $2^3/\sqrt{2} = 4\sqrt{2}2^3/\sqrt{2} = 4\sqrt{2}$. Lets describe this organization; we start with a flat layer of unit spheres so the centers are building the lattice in which we notice the closest packing of circles in the plane. Then we take the second and place the spheres in such a way that they are on top of the first layer and occupy the smallest possible distance between them, for achieving this the spheres have to fit in the hollows of the first layer. We should alternate, leaving some of the hollows empty, due to there is not sufficient space to fit a sphere into every hollow (fig21). Facing the third layer, we realize that this condition determines the position of the 3 layers with respect to each other.



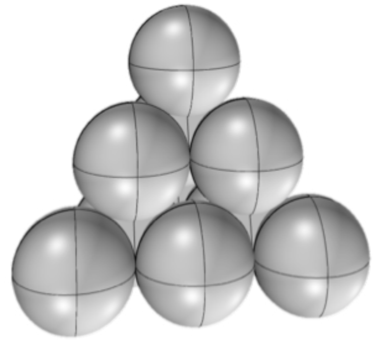
Graph 2.22 Lattice Relations



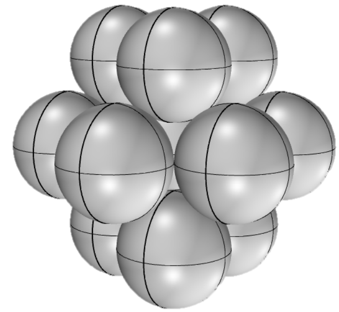
Graph 2.23 Lattice Configurations



Graph 2.24a First Sphere Arrangement



Graph 2.24b Second Sphere Arrangement



Graph 2.24c Third-Sphere Arrangement

Therefore, the spheres of the third layer are symmetric with respect with the first layer positions of the spheres hollows (Graph 2.24a). Another possible arrangement for the third layer is to locate the spheres over those hollows that were left free (Graph 2.24b&c). As we apply these translations in both directions the rhomboedral lattice arise as the packing of the spheres is completed, as in the plane only one type of arrangement of packing of circles reach the maximum density; this leads us to have two completely different arrangements of spheres.However there is one characteristic that all packing arrangements share: every sphere is in contact with twelve other spheres, six of them in the same layer, the other six are divided in two groups of three in the two adjacent layers. The research of closest regular packing in four and five dimensional space have shown that the lattices in higher dimensional space that correspond to the triangular and rhombohedral lattices no longer produce the closes packing of spheres.

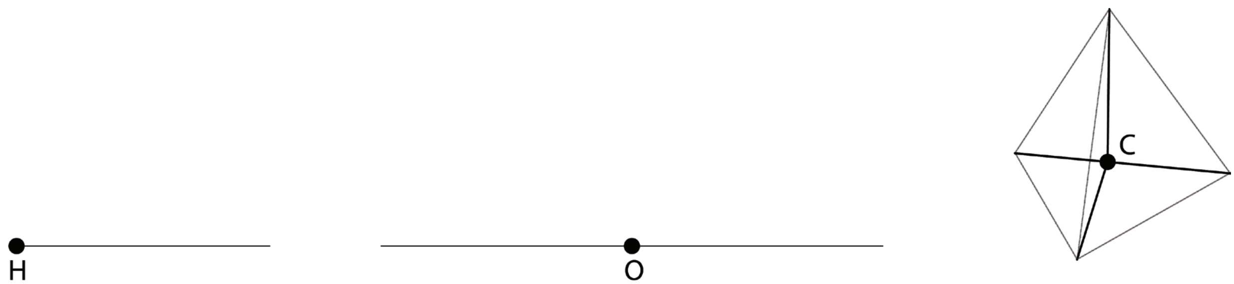
	C= minimum distance Between two points	Density of the Packing
Plane	$\frac{\sqrt{2}}{\sqrt{3}} = 1.075$	$0.289\pi = 0.907\pi = 0.907$
Ordinary space	$\sqrt[6]{2} = 1.122$	$\frac{\sqrt{2}}{8} * \frac{4}{3\pi} = 0.740$
Four-Dimensional Space	$\sqrt[4]{2} = 1.189$	$\frac{\pi^2}{16} = 0.617$
Five-Dimensional Space	$\sqrt[10]{2} = 1.074$	$\frac{\sqrt{2}}{60\pi^2} = 0.465$

The volume of the sphere of unit radius in four dimensions is equal to $\pi^2\pi^2/2$ and $8\pi^2/15$ $\pi^2/15$ in five dimensions.

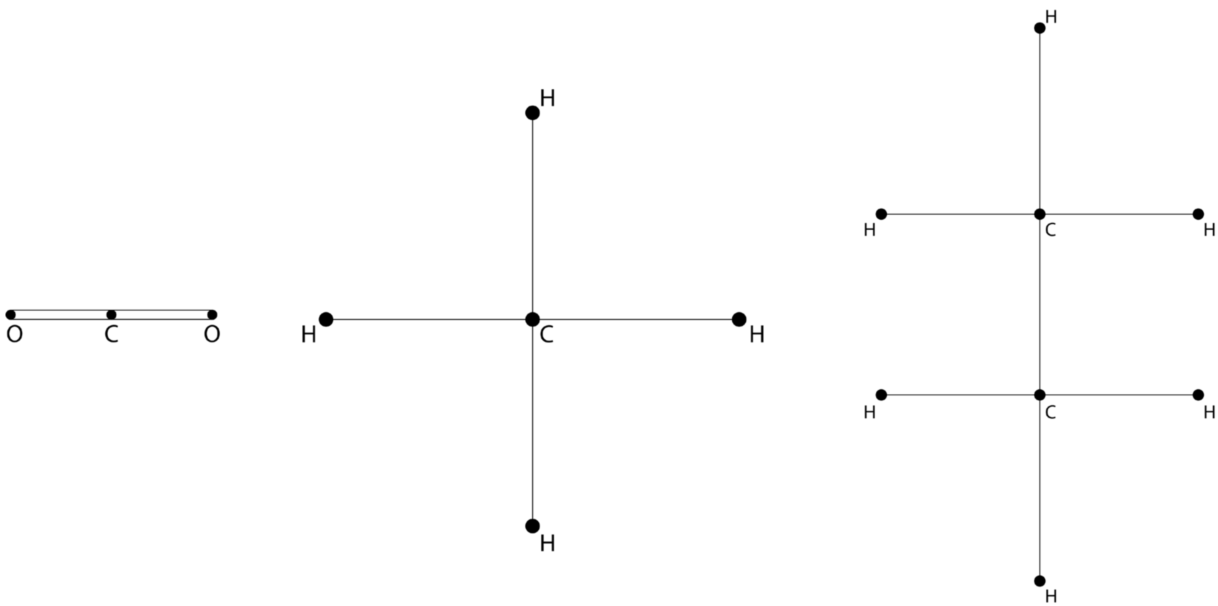
Crystals as regular systems of points

Crystals give us a particular approach to understand a system of points. For instance, crystallography shows the application for the theory of discontinuous regular systems of points. Each type of the system of points attached to each crystal and their physical behavior in terms of geometrical properties have two problems that we have to treat next. In order to define crystal lattices and their precise structure the use of Laue's method of the diffraction of x-rays by crystals came into place. The simplest picture we can make of an atom is a single point from which the arms that are equivalent to the valence of the atom, we must always assume that the spatial representation of the valence is symmetrically as possible. For instance, lets take the hydrogen *(H),* oxygen *(O),*nitrogen *(N)* and carbon *(C),* their valences are ; 1,2,3,4 respectively. In this case we are going to see how the atoms are represented by a system of points (Graph 2.25) *(H), (O)* and *(N)* are symmetrically lying in one plane, for the carbon atom the four arms point towards the four corners of a regular tetrahedron with the atom at its center. Now lets examine the representation of the structural formula of the carbon dioxide ($CO_2(CO_2)$, Methane

(CH_4(CH_4) and ethane (C_2(C_2 H_6H_6) (fig 24) in one plane and the most accurate spatial arrangements for the molecules of methane and ethane (Graph 2.26). The spatial configuration of the ethane consists of an axis that is connecting the *C* atoms in which the two tetrahedral can be rotated relative to each other. Its worth to wonder if whole crystals could be generated like molecules by attaching them more atoms.

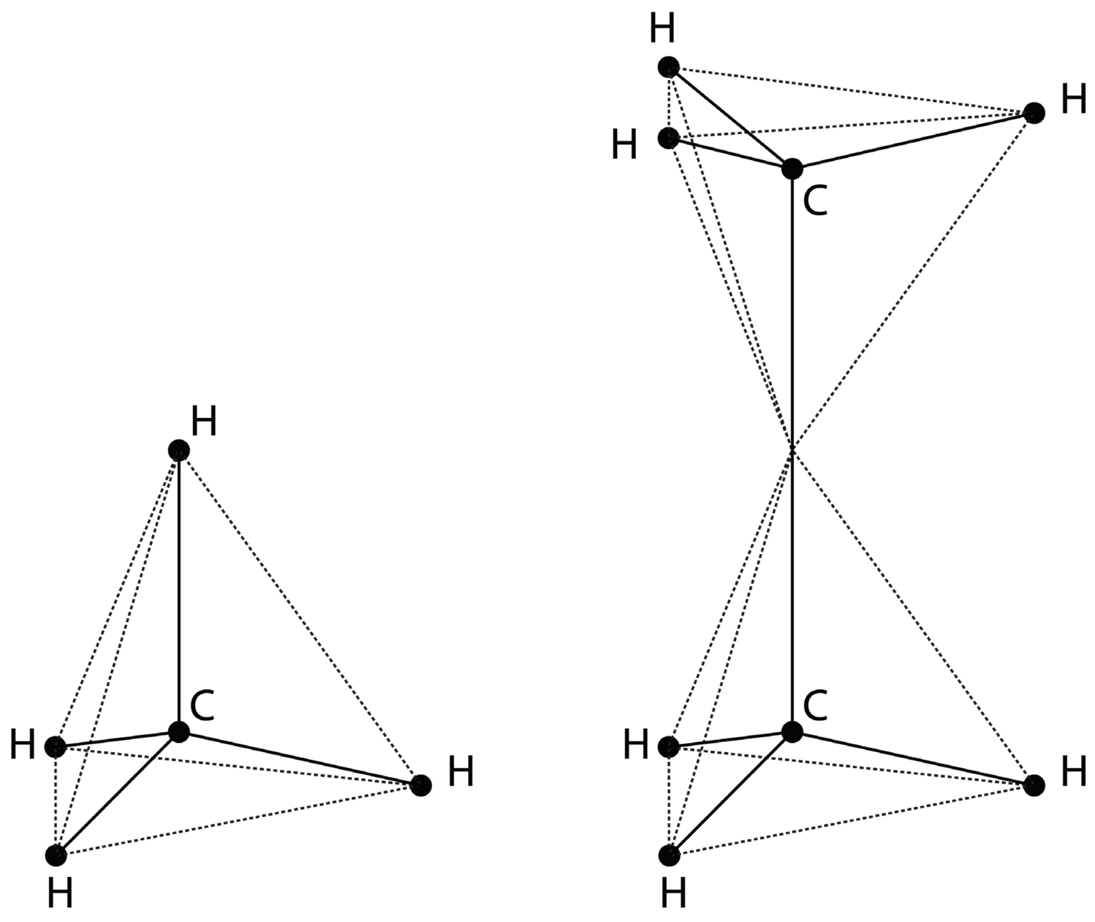


Graph 2.25 2D & 3D Representaion of Elements

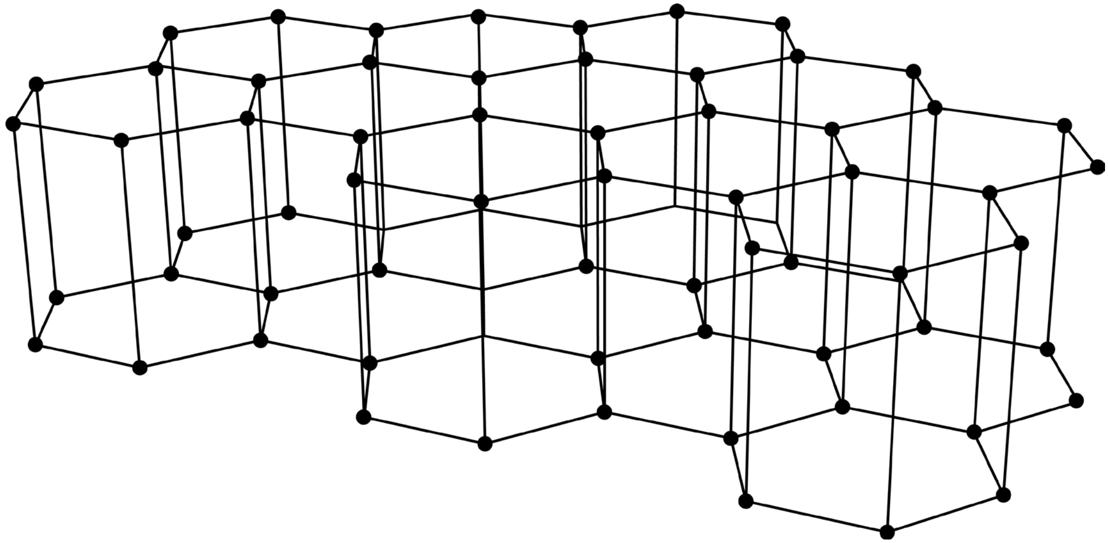


Graph 2.26 Atoms Representation in points system.

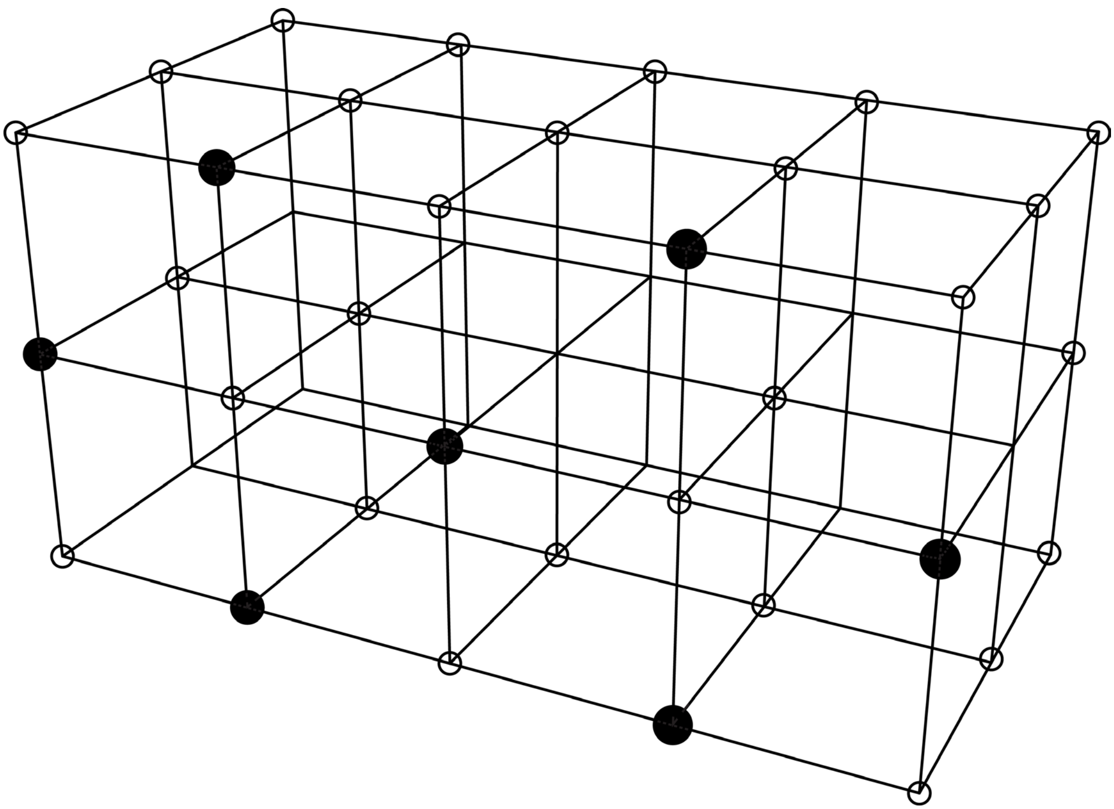
Lets go deeper in demonstrating this type of construction its better if we take in consideration crystals that consist of a single element; for instance the diamond and the graphite that contains of pure carbon elements. In the case of graphite, *C* atoms arms aren't symmetrically arranged and have different lengths the majority of them measure $3.4\times10^{-8}\times10^{-8}$ and one of them $1.45\times10^{-8}1.45\times10^{-8}$. So in order to discuss we will assume that the arms are coplanar, in this way its structure could be defined as a system of regular hexagons with one atom at each corner (Graph 2.29) this justifies for three of the valence bonds of each atom. The valence bonds that are still free are connected alternately with atoms of the upper and lower layer, the three layers become congruent and could be extended indefinitely in every direction. Another example of crystal composed from more than one kind of atom is the salt. Salt crystal is a cubic lattice, in which 2 of its components are occupying alternately its points, for the *CL* and *NA* atoms (Graph 2.29). The salt crystal lattice point has 6 neighboring lattice points, but because the *NA* and *CL* are univalent, the crystal can't be arranged as the previous examples.



Graph 2.27 3D Representation of atoms in space



Graph 2.28 Hexagon 3D lattice Arrangement



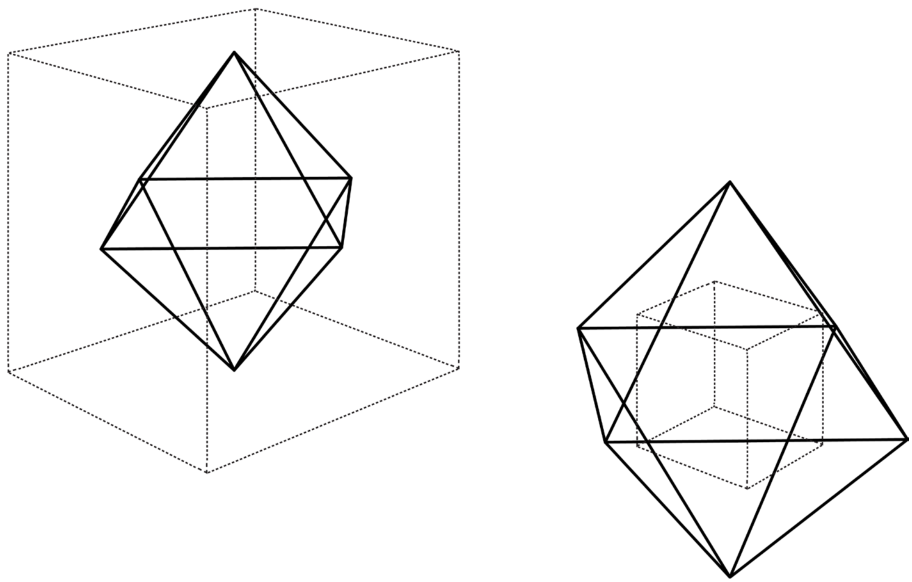
Graph 2.29 Square 3D lattice Arrangement

The regular Polyhedral

After analyzing the construction of the crystal classes we realized the construction of the regular tetrahedron and regular octahedron. Now lets define the general regular polyhedral besides the ones we have study in the crystallography. As general statement we require that all the edges and all vertices of regular polyhedron to be equivalent and all the faces to be regular polygons. In addition to these, the polyhedron can't have any re-entrant or concave vertices and edges. If this condition doesn't fulfill, it suggests that not all vertices are equivalent as well as the edges. Then, the sum of the face angles at a vertex has to be always less than $2\pi\pi$, if not that means that all the faces meeting at the vertex have to lie in one plane or some of the edges are re-entrant. What's more, at least 3 faces should meet every vertex and they have to be equal, this suggests that the magnitude of this angles to be less than $2\pi/3\pi/3$. Because of this reason, the only polygons that can occur as faces of a regular polyhedron are the regular polygons of 3,4 and 5 sides. If we check the angle of a regular hexagon is exactly $2\pi/3\pi/3$ and the angle of a *n-sided* polygon increases with *n.* For example, a regular 4-sided: the square, as we know the fact that this figure has right angles implies that only three squares can meet at the vertex without the sum of the angles at the vertex being equal at least $2\pi\pi$. In the same way, more than three pentagons can't meet at a vertex of a regular polyhedron. Consequently, the shape of a regular polyhedron depends on the number of faces meeting at a vertex as well as the number of the sides of each polygon forming a face. In the circumstance of equilateral triangles 3,4 or 5 of them can meet at a vertex, due to 6 of them make the sum of the angles at the vertex equal to $2\pi\pi$. Summing up, it can be 1 polyhedron bounded by squares and 1 by regular pentagons, equilateral triangles can form three types of regular polyhedral, bringing up the total number to 5. They are well known as the platonic solids.

Name of the Polyhedron	Polygons Forming the Faces	#Vertices	#Edges	#Faces	# of Faces Meeting At a Vertex
Tetrahedron	Triangles	4	6	4	3
Octahedron	Triangles	6	12	8	4
Icosahedron	Triangles	12	30	20	5
Cube	Square	8	12	6	6
Dodecahedron	Pentagons	20	30	12	3

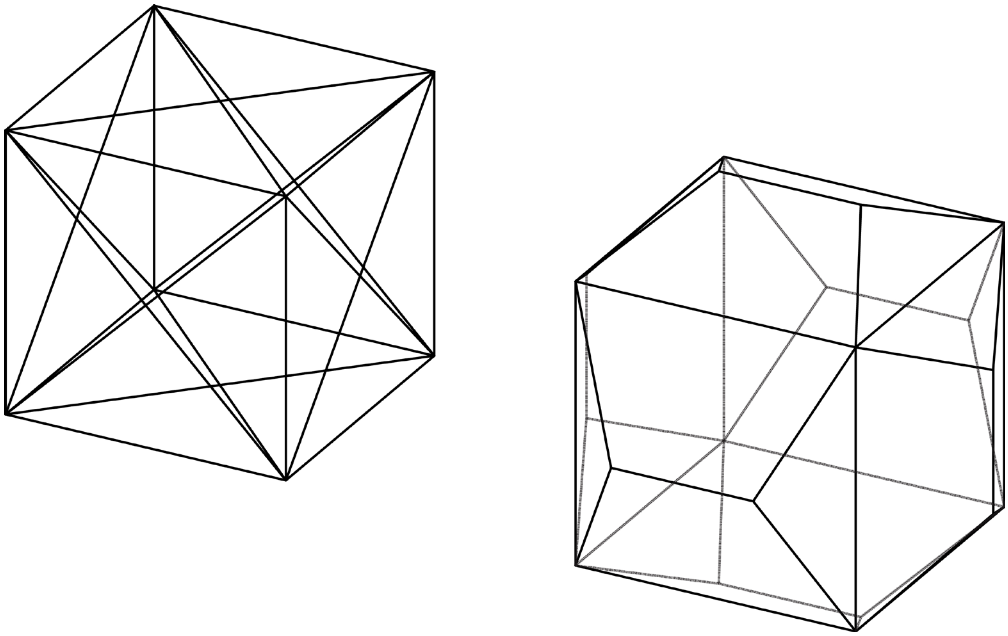
The relation the regular polyhedral have with the sphere is clear; all of them can be inscribed in this figure. For example, the planes that are tangent to the sphere at the vertices of any polyhedron must result in another polyhedron, which is conceived into self-coincidence by the motions of the group. Accordingly, the construction sets up a pairwise correspondence between the 5 polyhedral that are regular as well. Under this construction the octahedron leads to the cube (Graph 2.31). The relation between these two is because each of them has as many vertices as the other faces, both have the same number of edges and that the number of faces meeting at every vertex of both of them is equal to the number of vertices on each face of the other. We can see by these associations that the octahedron can be circumscribed. The icosahedral group relates in the same way to the icosahedron and the dodecahedron.



Graph 2.30 Relations Between cube & Octahedron

As we realized in the crystallographic studies didn't reveal this group due to the number 5 is crucial part on it and crystallographic classes can't contain 5 fold axes. Only when the construction is applied to the tetrahedron the output is going to be another regular tetrahedron. We found out that the tetrahedral group is a sub group of the octahedral group, as other types of relations between groups. For instance, that a regular tetrahedron is inscribed in a cube, so that the vertices of the tetrahedron are located at the vertices of the cube. Then the diagonals of the faces of the cube are its edges, in this way 2 different tetrahedral can be inscribed in the cube (fig29). As before, now the relation that appears is that the octahedral group is a subgroup of the icosahedral group, reason why a cube could be inscribed in a dodecahedron like a tetrahedron inscribed in a cube

A deeper inspection shows that 5 cubes like the ones mentioned before can be found in every dodecahedron and on each face of it, there is one edge of the cube and 2 cubes meat at each vertex.



Graph 2.31 Polyheral Figures

Regular polyhedral in three and four dimensions and their projections; as we just realized they are five polyhedral in 3D space. The only self-dual is the tetrahedron; the other ones are mutually dual in pairs. There is particularity that can explain this phenomenon, the fact that the dual pairs of polyhedral are symmetrical with respect to a point; it means that the vertices that come in pairs are symmetrically about the center as the edges and the faces. For instance, the continuous line that connects any vertex in a cube with the center encounters the cube at a second vertex. On the other hand, the tetrahedron doesn’t have a central symmetry; is not symmetrical with respect to a point, in this case the line that connects the vertex with the center is cutting the tetrahedron in the mid point of one of its faces. In order to continue we should define what is a Polytope: is defined as Polyhedra of *n-dimensional* space for $n \geq 1.\geq 1$. As mentioned before, for regular Polyhedra the faces are regular polygons, in the case of regular Polytopes in 4D; the boundary cells are regular polyhedral. Cells are 3D regions that build the boundaries along with the points, edges and plane surfaces. The number of regular Polytopes in 4D space is fixed to 6 and they are called *n-cell* if they are bounded by *n-polyhedra.* This is the essential information of the regular Polytopes in four-dimensional space.

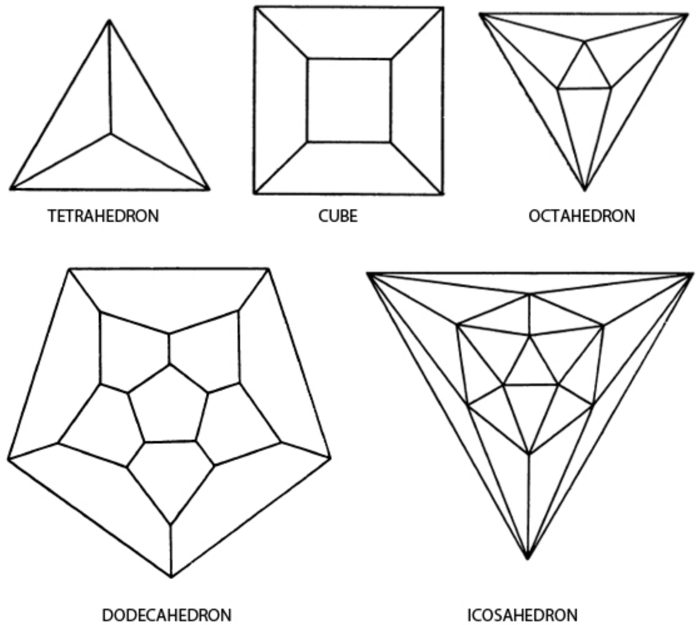
	Number and type Of boundary Polyhedra	Number Of Vertices	Duality
1. 5-cell	5 Tetrahedral	5	Self-dual
2. 8-cell	8 Cubes	16	Mutually dual
3. 16-cell	16 Tetrahedral	8	Mutually dual
4. 24-cell	24 Octahedral	24	Self-dual
5. 120-cell	120 Dodecahedra	600	Mutually dual
6. 600-cell	600 Tetrahedral	120	Mutually dual

By analyzing the table we recognize that the 5 cell is corresponding to the tetrahedron, on the other hand 8,16,120 and 600 cell are corresponding to the cube, octahedron, dodecahedron and icosahedron respectively. The 24 cell has two important characteristics; its self-duality and the fact that it is centrally symmetric whereas the regular 5 cell has no symmetry about a point. The study of higher dimensionalities shows that only 3 regular Polytopes can be found in any such space.

n- dimensional space, $n \geq 5. \geq 5$.

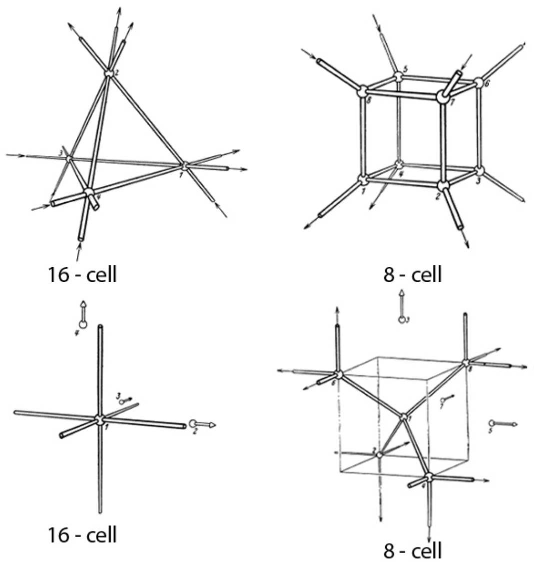
	Number and type Of boundary (n-1) Dimensional cells	Number Of Vertices	Duality
1. (n+1)-cell	n+1 n-cells	n+1	Self-dual
2. $2n$-cell	$2n$ $(2n-2)$-cells	$2^n 2^n$	Mutually dual
3. $2^n 2^n$-cell	$2^n 2^n$ n-cells	$2n$	Mutually dual

The 3D polyhedral that describes these 3 types of Polytopes are the tetrahedron, the cube and the octahedron; $n+1 = 4$, $2n = 6$, $2^n 2^n = 8$. Lets take a look into the projections of the Polytopes and regular Polyhedra into spaces whose dimensionality is smaller that one of the spaces these figures rely on. The projections will dramatically change depending on the center of projection and the chosen image plane; lets analyze the projections of the regular Polyhedra into a plane. In parallel projections the center is an ideal point, the advantage of this type of projections is the fact of representing parallel lines by parallel lines. On the other hand, the disadvantage is of making pieces of faces to overlap, to avoid this condition and to approach symmetrical projection we have to move the center of projection to a point near to the center of one of the faces and project into the plane of that face.

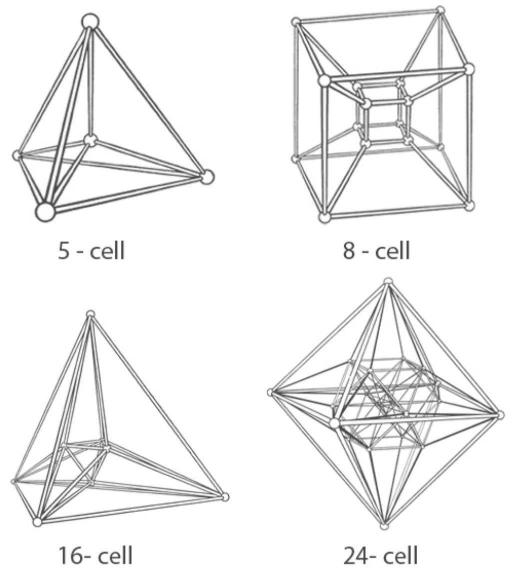


2.32 Points of Projection, by D.Hilbert. In : Geometry and the Imagination.

Let's have a look to the five regular polyhedral projections (Graph 2.32) as we were looking at the interior of them through a hole – the center of projection has to extent to infinity regardless of the choice of the image plane-. Now lets locate the center of projection inside the polyhedron, depending on the location of the plane, the image would be significantly altered, because of the planes will intersect the polyhedron. Now if the center of projection is at the center of the polyhedron, the group of rays that pass through the center are organized symmetrically, because of the group of rays could either be interpreted in the projective plane by looking at the "*straight lines*" of the group as points and the planes of the group of rays as "*straight lines*". This interpretation works under central symmetric polyhedral covering the projective plane. Lets examine the case of the tetrahedron, each straight line through the center gives 2 different image points that correspond to the 2 points that meet the surface of the polyhedron, in this sense the projective plane is covered twice. Lets review the case of the Polytopes; as we realized a set of polyhedral in space represents the boundary of the Polytopes, from which one of them is filled up simply by the others. Now lets have a look to the plane projections of this model(fig33-36). In figure 33,23 smaller octahedral fill the large octahedron; these ones are 4 different forms, generating 24 Polyhedra in total. For instance, in order to have a regular partition of the space in a Polytope projection, the center of projection should be moved into the center of the Polytope.



2.33 Cells Categories, by : D.Hilbert
In : Geometry and the Imagination.



2.34 Cells Categories, by : D.Hilbert
In : Geometry and the Imagination.

Thus, to produce a symmetrical model in the projective space isn’t possible, as the group of lines represent the projective plane, this occurs because the figure we are trying to represent is on a four-dimension and our representation is still fixed in a three dimension space so some of the symmetry is lost. In order to maintain some of the symmetry, the image space assumes analogous positions to the image plane, when dimensionality is one less. We have to two options for the projections, the first one; uses the boundary spaces for the arrangements (fig 35). The second one,we choose a space that passes through one of the vertices of the Polytope (fig36). The advantage in the first case is that the boundary polyhedron will be pictured without any distortion because is in the image space. The second case, the projection becomes symmetrical with respect to the vertex.

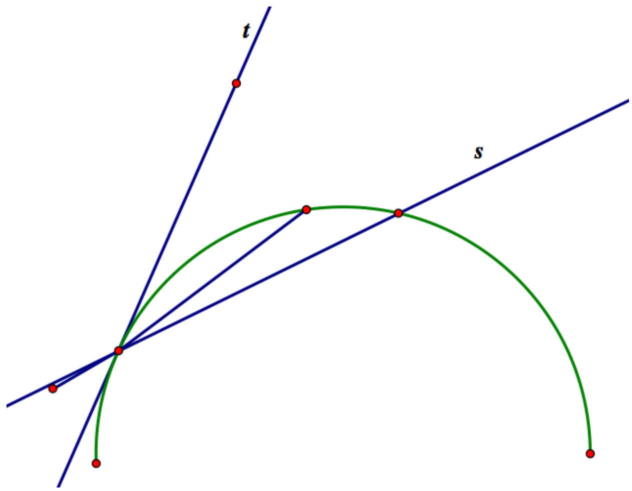
Lets see the 16 cell and the 8 cell produced by these 2 projection methods(Graph 2.32) The cell is portioned into 8 parts and the 8-cell in 4.

In the (Graph 2.35), we can notice two certain segments which extent to infinity, four of them have one boundary face - e.g.,1, 3,4 – that is retained into the finite part of space and from which they extent across the ideal plane until the opposite vertex –e.g., 2-. Three of the regions have 2 opposite edges that are finite –e.g.,1,2&3,4- but the faces aren't extending through infinitely faraway elements. In fig 39b, we note that the 16-cell produces a division into octants by a Cartesian coordinate system. Now, in the 8-cell(fig35a) all the regions that extent to the infinity have the same form.35b the regions edges contain the finite edges of point 1 figure with the exception of the edge 1 and 6. For the 24-cell(fig 36&37), the partition is in 12 Octahedra, with the exception of the octahedron in the center of fig38 all of them extent to infinity.

Differential geometry

In this case we will start by investigating curves and surfaces in vicinity of any one of their points. So the purpose is to make a comparison of the vicinity of such a point with figures such as; straight lines, planes, circles or a sphere. From analyzing the local differential geometry and its properties in the neighborhood of every one of its points, is possible to conclude certain essential facts about the general structure of the figure. We could agree that the differential geometry treats the problem Gauss and Riemann first posed, their concern was of building up a complete geometrical system on the concepts and axioms that only affect immediate neighborhood of each point. From this point of view, we can conclude that an effective description of physical reality must focus on the Riemannian geometry and treating non-Euclidian geometry.

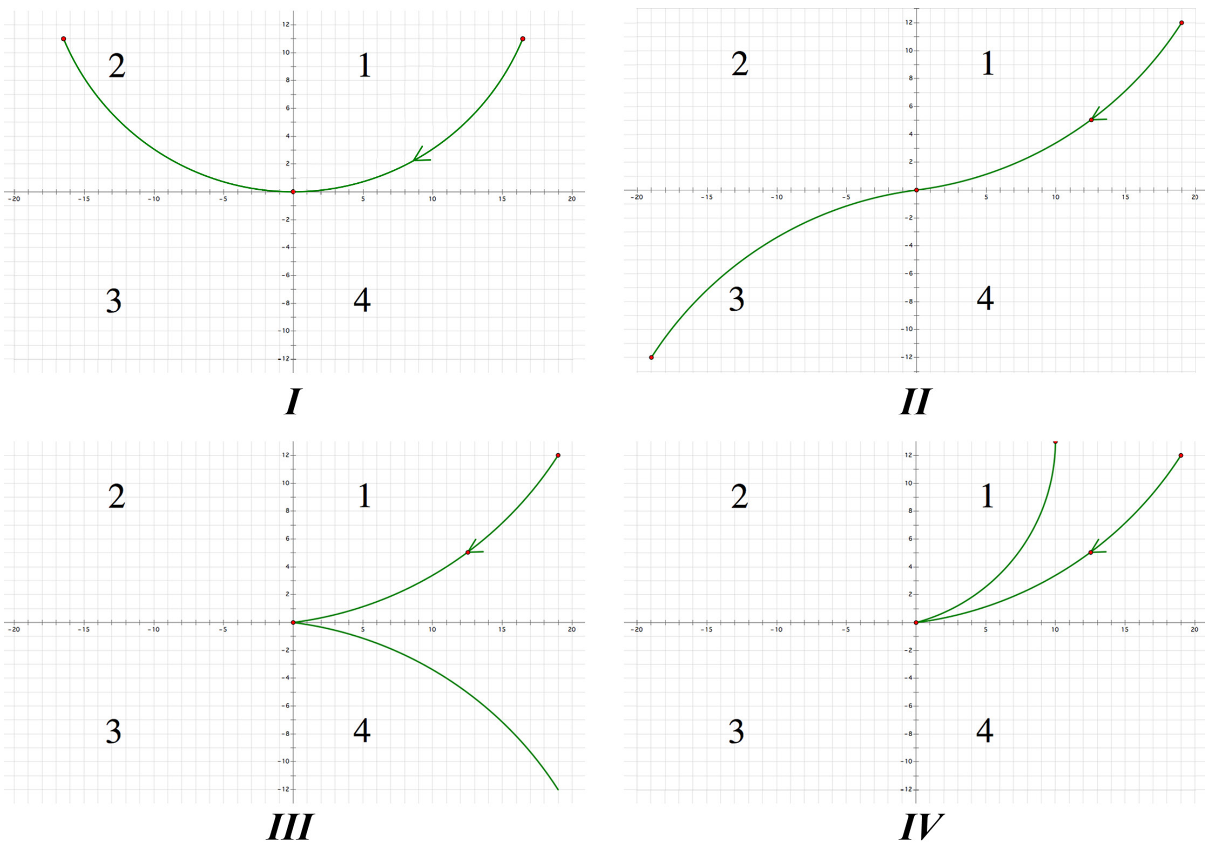
Plane curves



Graph 2.35 Secant, Tangent & Normal

In spite of analyzing the plane curves, we are going to focus on a small piece of the curve, which it doesn't intersect itself. A secant is a straight line that intersects the curve in two different points (Graph 2.35). Lets suppose the secant *S* rotates about one of its points, in this way the other point of intersection approaches a position *t.* Tangent curve appears as a straight line and the fixed point its called its point of contact. This tangent curve provides the closest approximation to the course of the curve at that point. The *normal* to the curve is a straight line perpendicular to the tangent at its point of contact. In this way, if we want to study any point of the curve; the tangent and the normal constitute the axes of a system of rectangular coordinates. This system leads us to study in a better way the behavior of the curve in a specific point, as we have notice the curve possesses a direction in our case lets fix one of the direction of the curve as the direction of the traversal. As we realize after drawing the tangent and the normal, our coordinate axes are dividing the plane in 4 quadrants, lets name them starting from number 1; which is the origin from which the curve moves toward the direction of the traversal (Graph 2.36). The tangent is separating quadrants 1,2 from the quadrants 3,4 and the normal separates quadrants 1,4 from 2,3. From the image we can recognize 4 different cases according to the location of the moving point after passing through the origin. In the case *I,* the point in which we are examining the curve is called regular, in the other 3 cases is called singular. Most of the points in a curve are regular. In the case *II,* the curve has a *point of inflection* and in cases *III & IV* is said to have a cusp (Graph

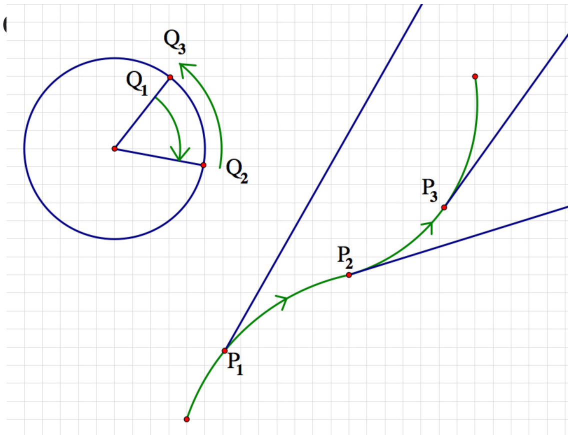
2.36) of the first kind (*III*) and the cusp of the second kind (*IV*). To check how the tangent changes its direction we will have to apply the gauss method. We proceed to establish a sense for the traversal on the curve, then in the same plane we draw a unit of circle, after the tangential lines of the curve are going to be represented by the radius of the circle parallel to the tangent keeping the same sense as the curve in that point (Graph 2.36). Every point *P* of the curve has a point Q of the circle; the points of the circle in this process are called the *tangential image* or *Gaussian image* of the curve. This Gaussian representation assigns only one point of the circle to each point of the curve. However, a single point in the circle not necessarily correspond to only one point of the curve, but to several points as long as the tangents have the same direction $-P_1P_3P_1P_3$ in fig40-. Now lets have a look to the direction in which the point of the Gaussian images moves, this one replicates the change in directions of the tangent in the curve. The four types of points on the curve are classified like this:



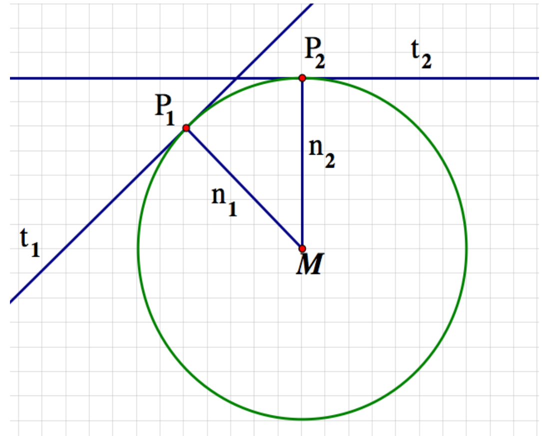
Graph 2.36 Categories Of Points On The Curve

I Regular Point; the point on the curve and its tangential image both stay in their old di-

rections.
II Point of inflection; point on the curve maintains the old direction.
III Cusp of first kind; image maintains the old direction; the point on the curve reverses it.
IV Cusp of second kind; both the point of the curve and the tangential image reverse their (

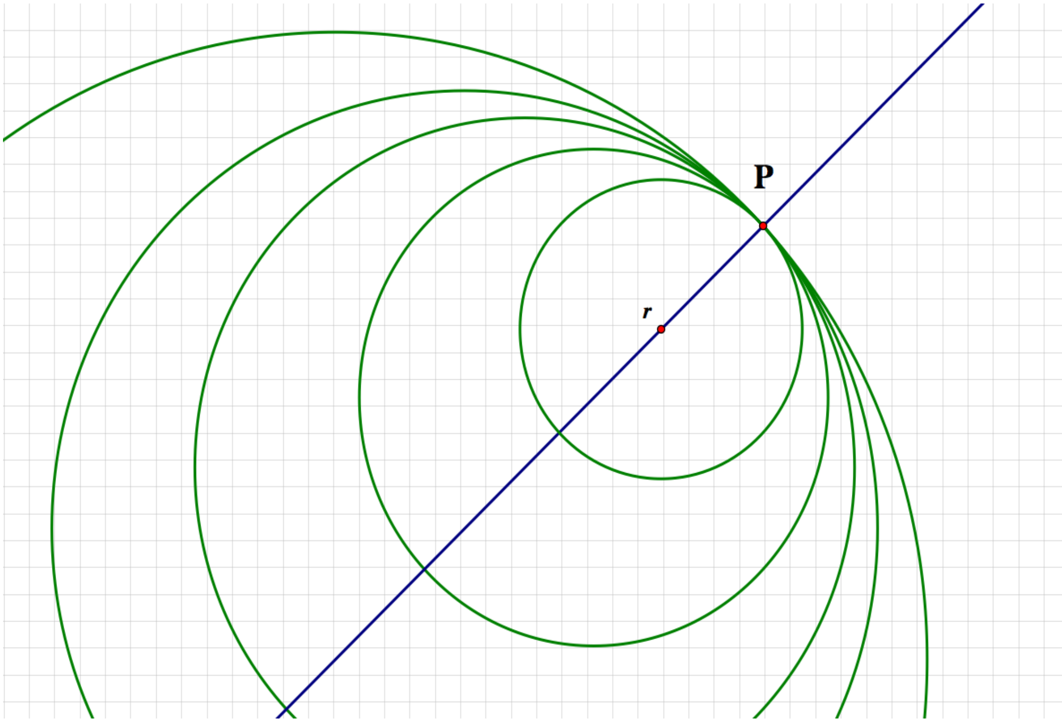


Graph 2.37 Gaussian representation

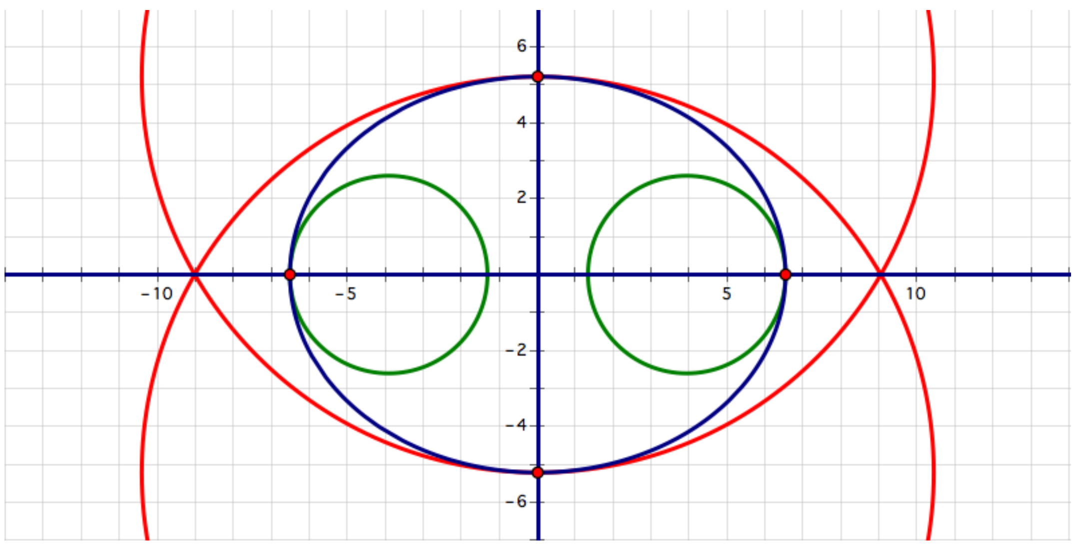


Graph 2.38 Curvature of curve

The next topic that is related with the Gaussian representation is about the curvature concept; (fig41) the tangents in the figure are T_1T_1 & T_2T_2, the normals $n_1\,n_1$ & n_2n_2 at 2 neighboring points P_1P_1 & P_2P_2 on a curve and the point of intersection of the two normal be at *M.* Therefore, the angle between the tangents is equal as an angle between the normals $\sphericalangle(T_1,T_2) = \sphericalangle(n_1,n_2) \sphericalangle(T_1,T_2) = \sphericalangle(n_1,n_2)$. Lets consider the ratio between the angle n_1,n_1, n_2n_2 when P_2P_2 is moving towards P_1P_1 along the curve, lets also consider the distance between two points of the curve, the ratio approaches a limit that is expressed in this way; $\lim_{P_1P_2\to 0}\frac{\sphericalangle(n_1,n_2)}{P_1P_2} = \mathcal{K}\lim_{P_1P_2\to 0}\frac{\sphericalangle(n_1,n_2)}{P_1P_2} = \mathcal{K}$, this limiting value $\mathcal{K}\mathcal{K}$ is named the *curvature* of the curve in point P_1P_1. The term *r* could be found in this way; lets draw a circle across P_1P_1 & P_2P_2 and two other close points of the curve, the limiting position of the circle appears when these 2 points get close enough to P_1P_1. Consequently, in the construction we realize that the center of this limiting circle is located at the limiting position of the point of intersection *M* of the normals and the radius is equal to *r.* from this analysis we deduce that this circle is called *the circle of curvature* of the curve at P_1P_1, as it s center is *the center of curvature,* its radius *r; the radius of* *curvature.* Now lets explore another possibility for finding the circle of curvature (Graph 2.39). As we see in the figure we have several circles through a point P_1P_1, they are tangent to

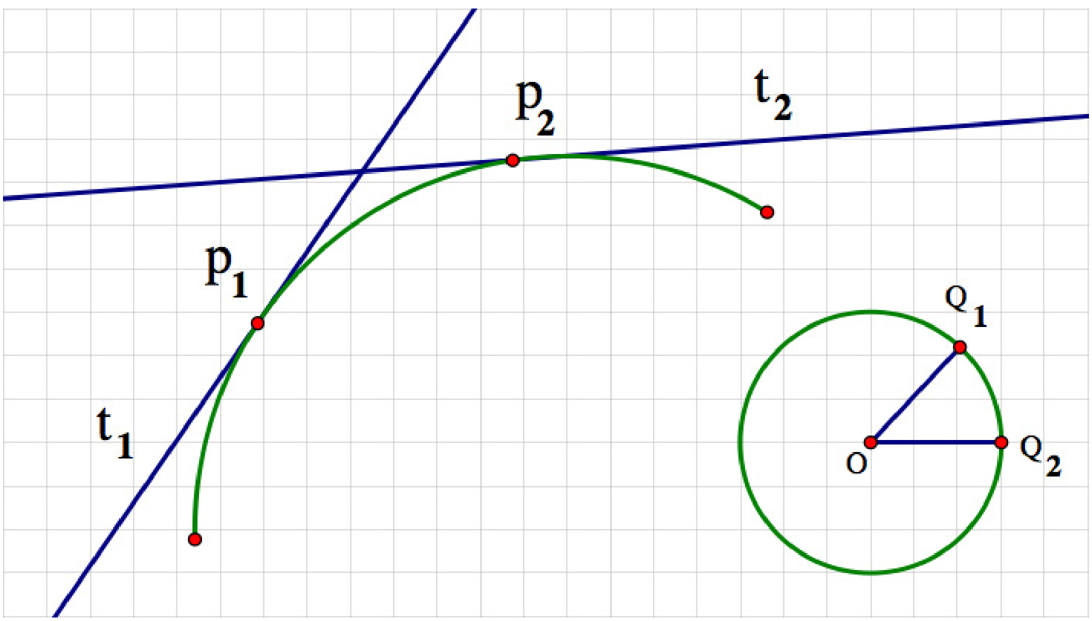


Graph 2.39 Center Of Curvature



Graph 2.40 Curvature Relations

the curve at $P_1 P_1$ Thus; their centers rely on the normal to the curve at *P.* If we check what's happening in the neighborhood of $P_1 P_1$ we find that the curve divides the plane in 2 parts. The circles are relying either in 1 or the other side of the curve in the neighborhood of *P, the circle of curvature* classifies this type of circles, depending in the size of the radius with respect to *r,* meaning that if their radius is greater than *r* it lies on one side and if its not, on the other side. Even the circle of curvature occupies opposite sides of the curve on the 2 sides of the normal, it crosses the curve at the point of contact, the singular points of the curve and the points of the circle of curvature don't intersect always along their path, this are called *isolated points.* For instance (Graph 2.40), the ellipse counts with four vertices, which because of its symmetry the circle of curvature cant cross the curve at these points. As we comprehended, there is a strong relation between the curvature and the tangential image of a curve. Let $Q_1 Q_1$ and $Q_2 Q_2$ be the tangential image of the 2 points $P_1 P_1$ and $P_2 P_2$of the curve(Graph 2.41).



Graph 2.41 Radius of Curvature

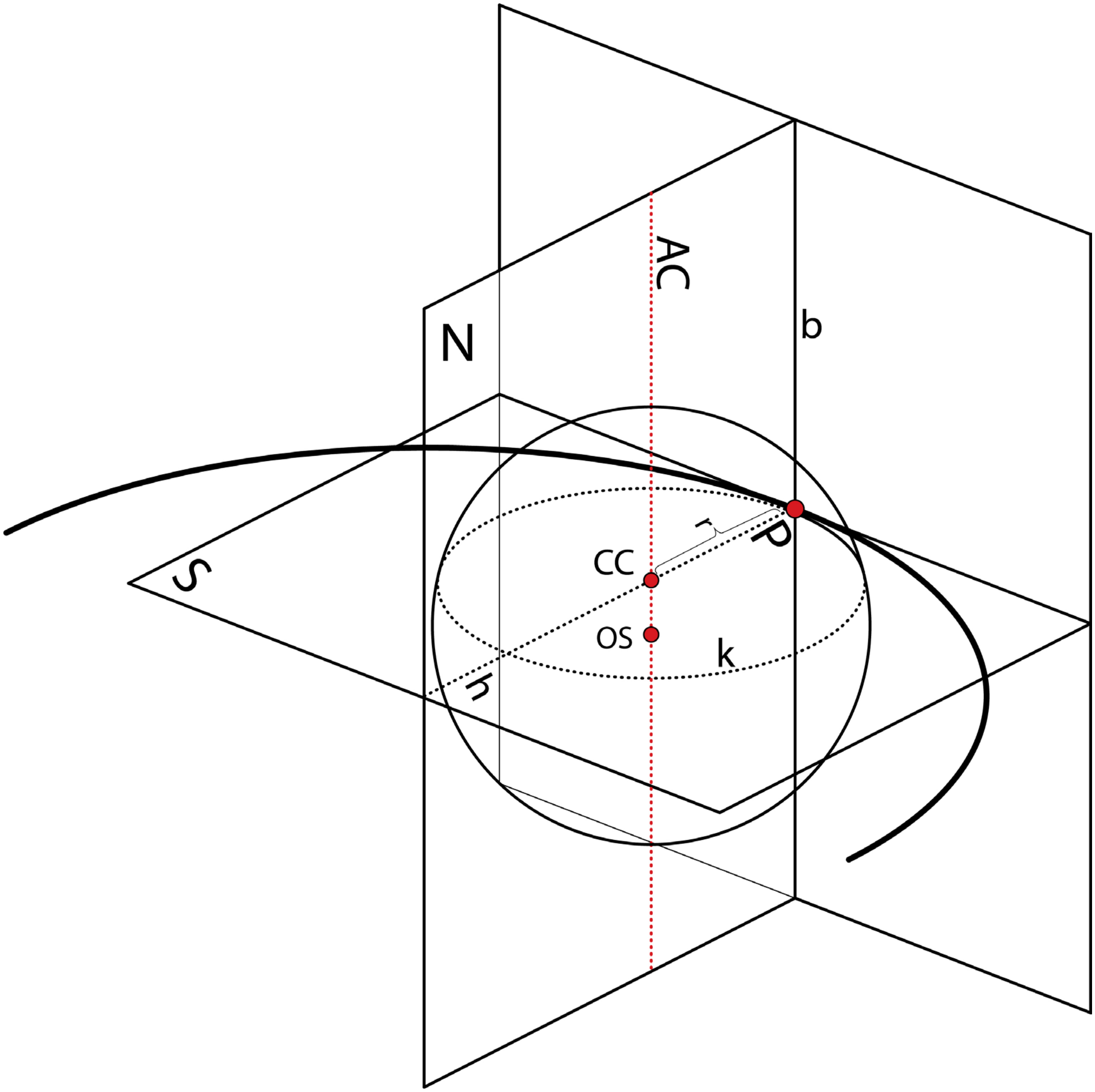
$< (T_1, T_2) = < (Q_1, Q_2) < (T_1, T_2) = < (Q_1, Q_2) = Q_1 Q_2 Q_1 Q_2$. Thus, the limit of the ratio between the length of a short arc of the curve and that of its tangential image is called *the radius of curvature*, when *the radius of curvature* becomes infinite in certain individual points. At these points the circle of curvature turn out to be an identical straight line as the tangent. Form this relation between the curvature of the curve and the tangential image we deduce that the curvature becomes infinite at a cusp of the first kind, for the cusp of the second kind we can't generalize.

To sum up, these concepts are arising new questions. For example, the curve could be defined by expressing its curvature as a function of the arc length and the function determines the form of a curve. Due to this method doesn't make a concrete reference to a particular system of coordinates; the arc length and curvature are named the *natural* or *intrinsic* coordinates of the curve. In the case when the curvature $\mathcal{K}\mathcal{K}$ is constant everywhere is when the circle has a radius $\frac{1\,1}{\mathcal{K}\mathcal{K}}$, when $\mathcal{K} = 0\mathcal{K} = 0$ is straight lines. Thus, circles and straight lines are the only plane curves of constant curvature. In addition, we can derive one curve from another, lets take all the centers of curvature of given curve forms a new curve named the *evolute* of the given curve, contrarily the first curve is called the *involute* of the second.

Space curves

Most of the information already described for the plane curves can be adapted to apply to curves in space. Our departure is going to be the same as before, we again get the tangent as the limiting position of the secant when one point of intersection moves to coincide with the other. In this case the 3D is different due to they are infinitely many perpendiculars to the tangent at the point of contact. These perpendicular lines can be drawn in the *normal plane* to find a plane that lies as close as possible to the curve near to the point under consideration; we recognize a similar process as the plane curves, in this case a plane that passes through the given point at the tangent and a near point of the curve that is moving along the curve towards the point of contact of the tangent, that is fixed. By doing this, we approach a limiting position in the plane; its name is the *osculating plane* in this precise point of study. The *osculating plane* has three coincident points in common with the curve and the curve generally crosses its *osculating plane* at the point of contact, therefore we find as well the tangent and the *osculating plane* is perpendicular through the given point of the curve to both the *normal plane* and the *osculating plane* is called the *rectifying plane.* We can interpret the three planes as coordinate planes in a 3D Cartesian coordinate system. Subsequently, the tangent is one of the axes in this system, the other two lie in the normal plane; the *principal normal* and *binormal*. The *principal normal* lies in the *osculating plane* and the *binormal* in the *rectifying plane(* Graph 2.42). The coordinate system receives the name of *moving trihedron;* this one is the analogous to the coordinate system made by the tangent and the normal in the case of the plane curves. The space coordinate system is defined by eight regions named; octants – in the plane where named quadrants-. The *moving trihedron* recognizes eight types of points in a curve, as for the planes, in this case only one point is considered regular and the others occur at isolated points. Lets define the Gaussian representation for three dimensional curves, we proceed and draw a sphere of unit radius, to every tangent of the curve there is a radius of the sphere being drawn in the same direction, the tangential image of the point on the curve is the tangent extremity on the surface of the sphere. On the other hand, if the *binormal* or the *principal normal* were used instead of the *tangent,* we would get two more curves on the sphere. The connection between these three *spherical images* and the original curve can be seen in the tangential and *binormal* indicatrices, which together they characterize the eight types of point of a curve when the *tangent*, the *point on the original curve* and the *binormal* move on continuously or reverse its course and we combine the outputs, we will arrive to those eight cases. Lets review the concept of curvature for the space curves let $t_1t_1$and t_2t_2 be the tangents at two neighboring points p_1p_1 and p_2p_2 of the curve, we arrive to this quotient $< (t_1t_2)/p_1p_2 < (t_1t_2)/p_1p_2$ as p_2p_2 approaches $p_1.p_1$. This quotient approaches a limiting value, which we call the *curvature* of the curve at $p_1.p_1$.

In the plane curves the limiting of the point of intersection of two normals is related to the *curvature* of plane curves; in this case a point is conceived. For space curves is not a point, but a straight line. This line is called the *polar axis* of the curve at this point, it is parallel to the *binormal* and is located in the *normal plane,* the *center of first curvature* is that in which the polar axis and the principal normal intersect in a point, now the distance *r* between the corresponding point of the curve and the center of first curvature. Lets continue with the similarities found in the plane. For example, the Gaussian tangential indicatrix is related to the curvature in the same ways as in the plane , the proof is similar to the one we employed before for the plane, we start by checking the angle between two osculating planes, or for the same purpose the angle between the binormals at two points of the curve. Therefore, if we divide the angle by the distance between the corresponding points of the curve and then we let the points move into coincidence. Then we found the limit *t* of the quotient that is called the *torsion (second curve)* of the curve at the given point of the curve. We obtained the *first curve* by a limiting process by using three neighboring points on the curve, for the *second curve* we need four points, from these four points we can build a sphere. Accordingly, we take the limiting position of the sphere that passes through four neighboring points of the curve as they move to coincide, in this way the *osculating sphere* is that one that assumes the limiting position. There are various peculiarities to point out; the tangent to the curve is as well tangent for the *osculating sphere* at the point of contact, the *polar axis* lies on the center of this sphere. Now if we want to find out the distance between the center of the *osculating* *sphere* and the center of curvature we proceed to calculate it in this manner $\frac{1}{t} \cdot \frac{dr1}{dst} \cdot \frac{dr}{ds}$, where *ds* and *dr* are the differentials of the arc length and of the radius of curvature respectively. We have also to mention *s,r* and *t* in the case of space curves these ones are called the *intrinsic* or *natural parameters* of a space curve. Lets have a look to this theorem; we will find one and only one shape for a curve in space; therefore *r* and *t* be given functions of *s* on that curve. Then we will get a straight line if $\frac{11}{rr}$ is identically to zero. If *r* and *t* are constants different from zero we arrive to circular helices. For the curves on a sphere, the condition is more complex, the sphere that conducts the curve must coincide with the *osculating sphere* at all the points of the curve and for this reason the radius of the *osculating sphere* is a constant $r^2+(\frac{dr}{ds})^2 \cdot \frac{1}{t^2} = const.r^2+(\frac{dr}{ds})^2 \cdot \frac{1}{t^2} = const.$



Graph 2.42 Moving Trihedron-Coordinate System

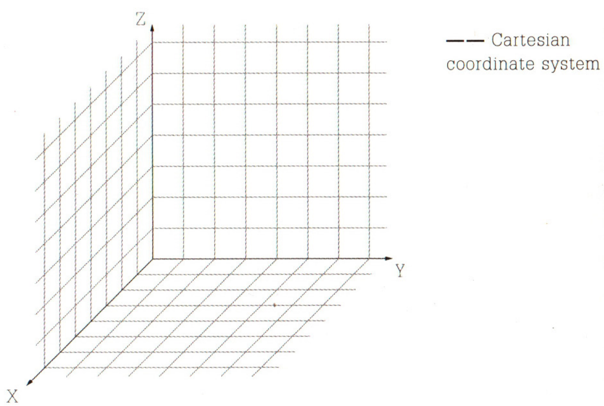
P: The point under consideration
S: Osculating Plane
N: Normal Plane
R: Rectifying Plane
t: Tangent
h: Principal Normal
b: Binormal
k: Circle Of Curvature

OS: Center Of Osculating Sphere

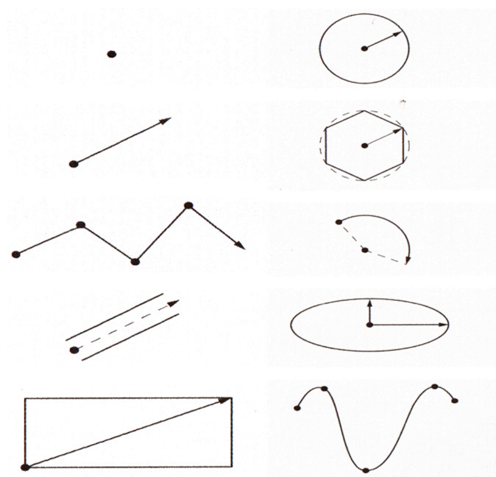
Chapter Three

CAAD Design Elements

The model oriented method enables to extend a design in 3 possible directions having a huge range of editing options and helping the designer to take more accurate decisions. As the architectural language changed with the appearance of CAAD systems is worth to define its principle design elements. CAAD systems take as basis the point, this object is capable of generating all other objects. Is defined as a zero-dimensional object and it has only one pair in the coordinate system.



3.1 Caartesian Coordinate System, by :
M.Hemmerling. In : D. design maual.



3.2 Creating CAAD objects, by :
M.Hemmerling. In : D. design maual.

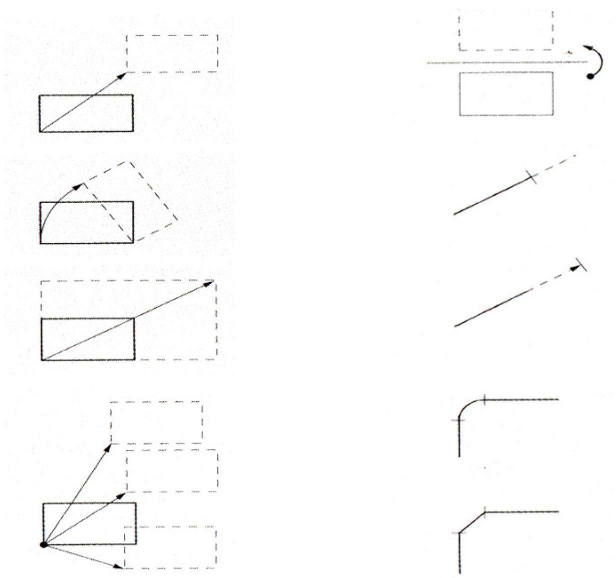
Line straight curve; defined by entering start and end point, or by specifying start point, angle and length.
Polyline; continuous series of lines, defined by start point and additional successive points.
Rectangle/square; are drawn by determining the start point and then defining the diagonally opposite second point.
Circle; determined by its radius or defining the diameter, also as determining 2 tangent points and the radius or 3 points.
Polygon; is a closed angular figure composed at least by 3 points or more.
Circular arc; its defined by start point , end point, centre or angle.
Ellipse; defined by 2 local points and 2 radii.

Free-form curve; they are specified by approximation or interpolation, whereby freely defined points are connected by a curvilinear line.
Spline; is an example of free-form curve running through a defined number of points, connecting these as homogenously as possible.

CAAD systems provides to the designer in an overall two main tools; the possibility of Creating Objects and Editing Objects. Under the scope of creating objects the necessity of understanding geometry becomes essential, the basic knowledge of geometrical properties in o bjects not only allows us to build single elements, but to wisely choose the appropriate tools for the design purpose. Consequently these are the main geometrical functions in CAAD systems.

Delete; delete objects from the drawing.
Move; changes the position of one or more objects.
Rotate; rotating objects around one based point at a defined angle.
Scale; enlarging or reducing the size freely, or at a defined factor.
Copy; generates identical copies of an object.
Mirror; mirrors objects on an axis of reflection.
Crop/trim; crops objects by using one or more cutting edges.
Stretch; elongates objects towards one or more reference edges.
Shear; divides into separate parts.
Rounding radius; connects two objects that stand at an angle to each other with a tangential radius.

As a support for the CAAD tools, various design aids enables a precise control when editing an object. For instance, the usage of snap functions permits the designers to accurately select a point in the drawing, that is linked to predefined geometrical objects. To talk about three dimensional space in CAAD systems we have to realize that 3D modeling can be explained in two ways; one as a geometric description with mathematical and physical properties, in which the designer can define proportions, dimensions and objects in the space and the second one; that is related with the phenomenological description, and explains how is the human being experiencing a particular space. The purpose of CAD is to shape 3D models in which the geometrical description is accurate and offer a clear statement about formative qualities of the design.



3.3 Editing CAAD objects, by : M.Hemmerling. In : D. design maual.

PHYSISCAL & DIGITAL MODELLING

A model establishes complex relationships in a design of a building, therefore is mandatory to understand the virtues of the different kinds of models. The designer is forced to have a conversation with the model during its process, in the case of a physical model, the designer is feeling the materials by tactile contact, and is joining them in order to achieve personal preferences and to express a formal idea of his project. In this case, the model opens wide new questions about spatiality in a project and becomes an excellent tool to examine directly details that were drawn. On the other hand, Digital models are helping the designers to visualize a particular state in the design process. What's more, the model is created in scale 1:1. Therefore, the designer is able to explore and examine it completely or in detailed sections, the digital model can be enhanced by adding new information and can be detailed without loosing its fundamental purpose. One feature that digital models have is the capacity of having multiple variations in terms of geometry and appearance, due to the manipulation options CAD systems offers. The dialogue with the model is still maintain in CAD systems, evaluating permanently the design in a 3D space and questioning the design while working on it, this last point allows the designer to evaluate the digital model as a whole. A digital model, also offers different qualities and level of information depending on the specific task and reuirements needed. For instance, a wireframe model compose a line around the geometric boundaries of a 3D object, the purpose of this model is to present an abstract geometric representation of the edges. The surface model; is defined as geometrical body composed by surfaces, the model can be used for dimension calculation and basic cross sections, this kind of model is suitable for more complex free-form geometries. Solid model; is one of the most holistic representation of a 3D object. Its defined by closed solid bodies, that contain information about volume, mass and centre of gravity. They are two types of solid models, the first one is BREP (Boundary Representation); it describes a 3D object in relation to the orientation of its surfaces, lines and corner points. The second one is CSG-models and are based on geometric primitives with a defined mathematical function that can be substracted, joined or intersect in order to produce more complex geometries.(Boolean Operations)

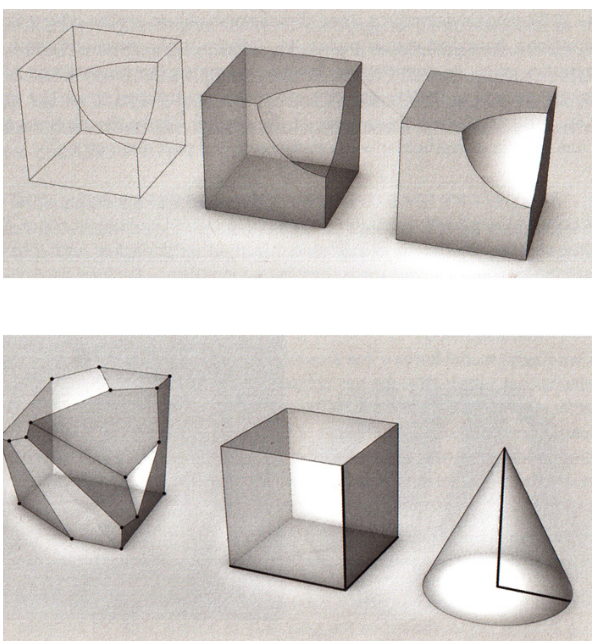
CREATING A 3D MODEL

In the case of 3D modeling, the objects relate to all three spatial coordinates (x,y and z), therefore; points, lines, surfaces and solids are defined by spatial coordinates. Geometry must be understood in order to create any spatial design concept, the exact definition of regular geometries helps to achieve an accurate proportion and dimension. In fact, properties as cutting and combining regular bodies allow the designer to expand the formal language into more complex geometries. As an example, is worth to summarize the most relevant characteristics of 3D solids and surfaces on the basis of their geometry. Primitives; are those in which the designer can select from a number of objects offered,(sphere, cylinder, cone, cuboid). And also more complex ones like ellipsoid and torus.

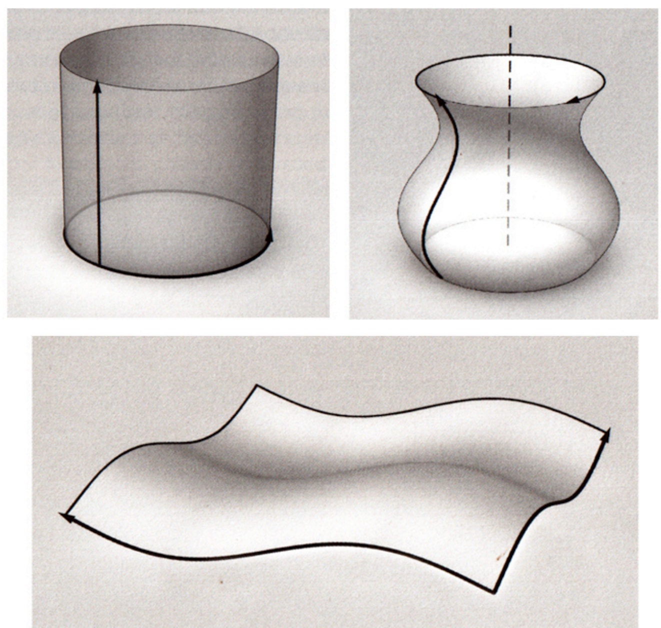
Polyhedron; is defined as a solid composed by flat faces and straight edges, for example: is a prism that is composed by a polyhedron base and an equal one on the top, the two faces are connected by joining faces and the corners are connected by straight, parallel lines that form a rectangle or a parallelogram. Pyramids; have as a base a polygon and a central point, each edge of the polygon and the apex form a triangle. Platonic Solids; these can be defined as regular, convex polyhedrons, its faces are formed by identical flat polygons, with the same number of faces meeting at each vertex. In total they are five platonic solids by the number of their faces: Tetrahedron (composed of four triangles), Hexahedron (composed of six squares), Octahedron (composed of eight triangles), Dodecahedron (composed of twelve penthagons), Icosahedron(composed of twenty triangles).

TYPES OF SURFACES

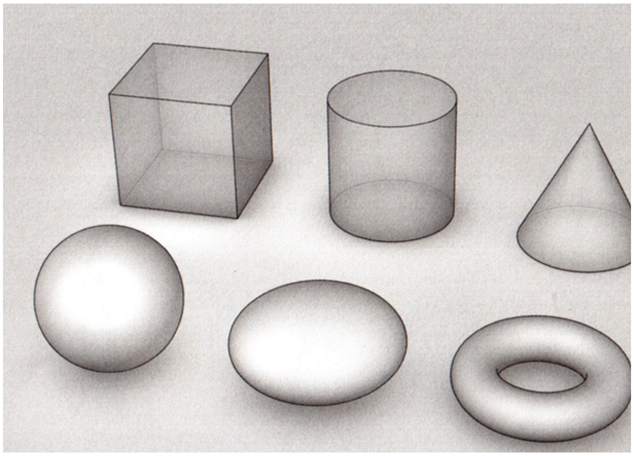
In this case moving a primitive form along a defined path generates the surface. The classification is done by the method of movement underlying initial geometry (linear, circular or spiraled movement). Surface of extrusion; 3D objects can be created from one or two-dimensional objects by extrusion, defining a height value. It works by moving a base geometry along a straight line into the third dimension. Surfaces of revolution; these kind of surfaces are created by rotating a curve around a central axis. It defines a circular geometry around the center of the surface of revolution. It can be defined as a closed geometry if its rotating 360° or an open one due to the choice the designer has to use it as a semicircular surface (180°). Depending on the original geometry of the curve, the result can be a single curved or double curved geometry.



3.4 Categories of models, by : M.Hemmerling. In : D. design maual.



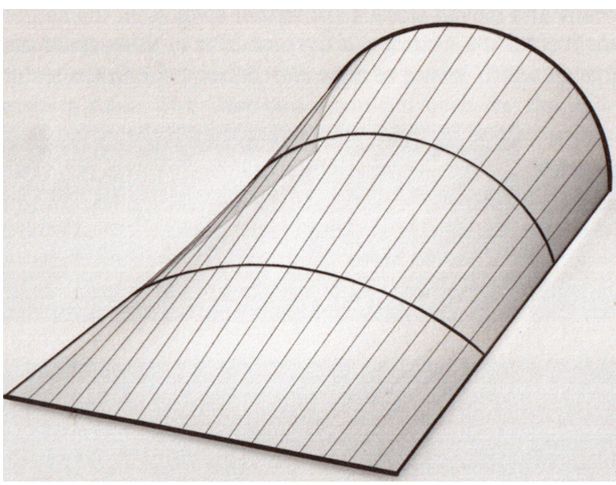
3.5 Extrusion,Revolution and Translation surfaces,- by : M.Hemmerling. In : D. design maual.



3.6 Solid CAAD Primitives, by : M.Hemmerling. In : D. design maual.

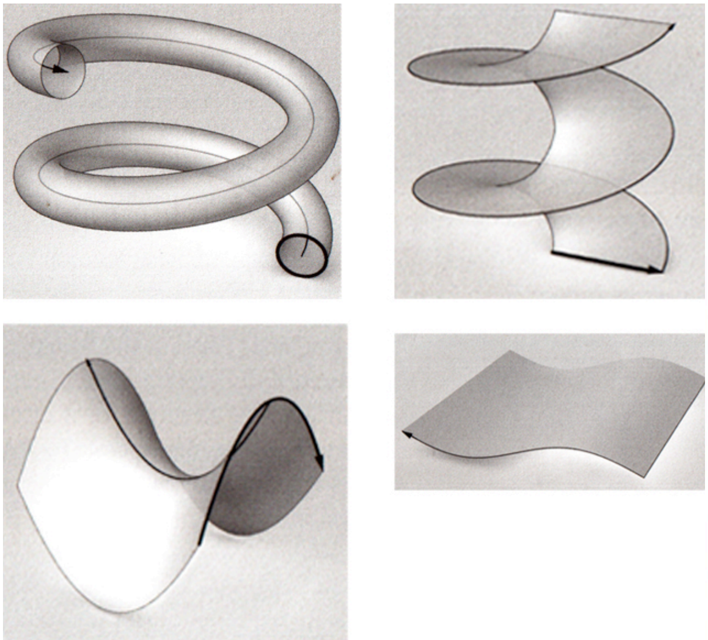
Surfaces of Translation; these are created by two boundary curves that encounter in a common point, they are drawn by a parallel translation of the first boundary along the second. Ruled Surfaces; translating a parallel line along a curve creates these type of surfaces. Saddle Surfaces; they are also called hyperbolic paraboloids and are formed with boundary curves, similar to ruled and translation surfaces.Helical Surfaces; these are based on helical or spiral basic geometry that describes a continually rising curve that leads along a cylinder surface.

Pipe surfaces; are created by moving a circle around a curve, with more complex functions the designer is able to change the diameter during the movement so the section can be reduced or increased. Free Form Surfaces; their characteristic relies on being homogeneous surfaces with soft transitions. They are free of restrictive conditions of regular geometries. With the implementation of 3D modeling programs the designer is able to have a comprehensive and precise description of these complex geometries. Their surface matrix is established as U-V, that in simple terms is defining its two directions. The different types of free-form curves are divided in three; Bezier curve, B-Spline Curve, NURBS Curve, these curves are defined by control points that are being connected by straight lines and create a control polygon. They are two possible ways of creating curve geometries; the first one is interpolation method, in this method the designer choose where are going to be the points than later will be connected by a free form curve. The second method is called approximation; is done by selecting the position of the control points and then the geometry of the curve is calculated.

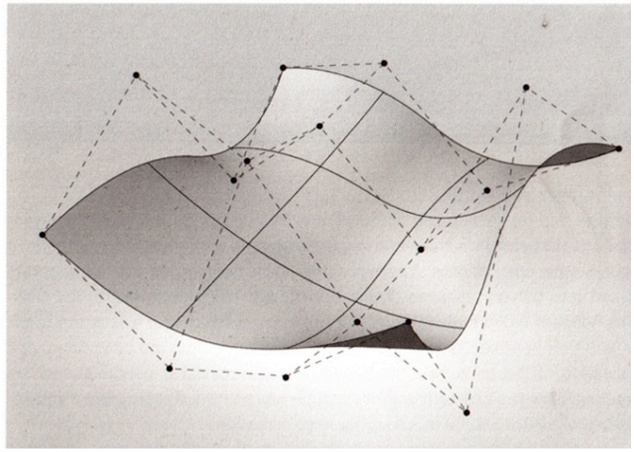


3.7 Loft Surface, by : M.Hemmerling. In : D. design maual.

Bezier Surfaces; these kind of curves are based on interpolation method; the final definition of the surface depends on the number of control points. B-Spline; they consist of the joining of Bezier curves with a soft transition.NURBS Surfaces; it stands for Non- Uniform Rational B-Spline, is an improvement of the previously described curves. They are also defined and controlled by control points.Loft Surfaces; the loft function connects at least two cross section curves, finding an homogenous surface progression. The final geometry is covered by a continuous enveloping surface.



	Control point	Degree	Weigthing
Bézier	×		
B-Spline	×	×	
NURBS	×	×	×



3.8 Pipe,Helical, Saddle and ruled Surfaces- modeling techniques applied to free form surfaces.
by : M.Hemmerling. In : D. design maual.

EDITING OPTIONS

The importance of having editing options in surfaces is helping us to enhance or modified our 3D model, one of these editing option are the Boolean operations, they are working on the principles of the set theory and work with logic operators; AND, OR NOT. The operators make possible to overlap solids in order to create new ones. The edition options of 3D modeling allow similar modification options as the ones described before.

Split and Trim; Partial areas of surfaces can be deleted or separated using these functions. The surfaces can be divided along their cut edge or taking as a reference an area made with curves. The splitting option permits the designer to separate the surfaces and preserve them for future editing. On the other hand, trimming deletes the surface selected.

Fillet and Chamfer; fillet allows the user to connect two surfaces that meet on an angle creating a rounded transition.
Chamfer; creates a surface transition with a sloped surface that joins two initial surfaces.
Offset; the offset editing option creates a parallel surface in direction of the surface normal with a previously established distance from the original surface.

NURBS

The study of free-form curves in CAD software is divided in three major clusters; Bezier Curves: these ones rely their geometrical constructive properties on the Castelijau algorithm. B-spline curves on the other hand are being defined and controlled by an outer polygon in which the curve is embedded. NURBS (NonUniform Rational B-Spline) process the creation of the curves by manipulating weights that are correlated with the control points, this type of curves offer the designer the possibility to draw the most complex freeform curves. Digital making of curves has a strong relation with the way designers used to draw long curves way before we could use CAD software. Their methodology back in the time, consisted in the use of mechanical aids; they were bendable rods made out of metal or wood by which the final shape of the curve was controlled by certain points in which the rod was fixed. This approach has strong similarities in the way digital curves are being made; the three categories of digital curves share the fact that are being manipulated by control points, which are associated to a control polygon. The computer allows the designer to input certain control points and computes the smooth curves in a faster way than drawing them by hand. What's more, changes in the shape of a curve are easier to modify by relocating the control points, than to displace manually the number of control points. They are two approaches for designing curves with the help of control points:

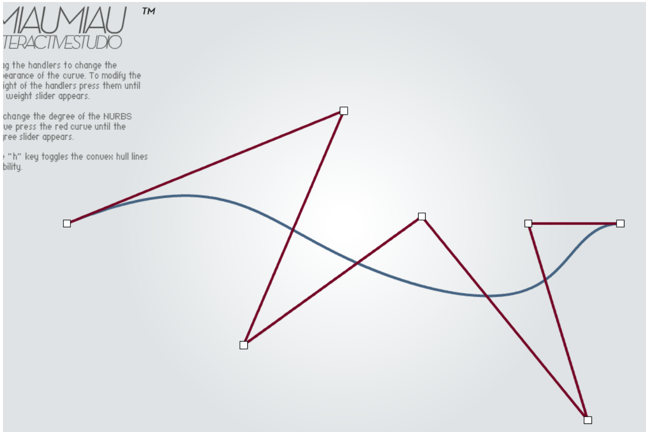
Interpolation

The user defines the number of points, shape and their tangent directions. Consequently an algorithm is able to compute automatically a curve that passes through these points. Therefore, interpolating them.

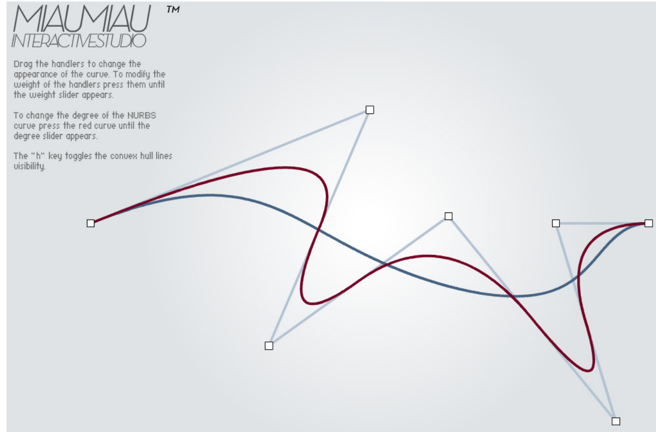
Approximation

In this case the designer draws a control polygon from which an algorithm computes the free form curve that resembles the form of the control polygon.

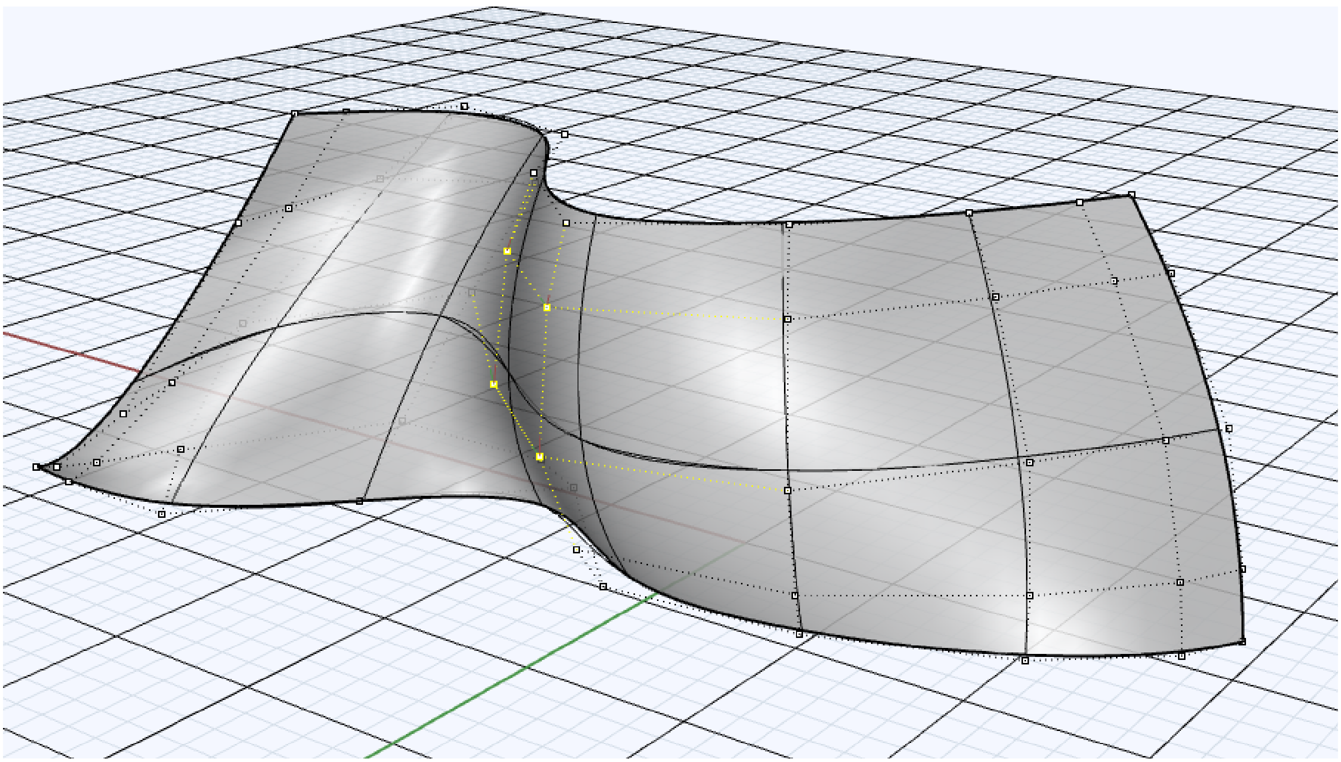
As we have notice, the advancement in digital modeling has allowed architects to overcome the limits of Euclidean geometry and isolated volumes represented in the Cartesian space for a more fluent geometry of continuous curves and surfaces; presented mainly in designs of contemporary architecture.These complex curvilinear surfaces are described mathematically by the name of NURBS: Non-Uniform Rational B-Spline. NURBS Curves and surfaces became appealing and essential to Avant-Garde architects, due to its capability to control their shape in an easy manner by manipulating the control points, knots and weights. Fundamentally, the shape of NURBS curves is ruled by controlling the location of the control points that not necessarily have to follow the curve itself, excluding the endpoints. The extension of each segment that composes a NURBS curve is determined by the Weights. The weights influence in the shape of the curve by dragging the curve towards or away form the control point. Its worth it to state that a modification on the weight of a certain control point has only a local influence over the total shape of the curve.



3.9 NURBS Curve,by : Interactive studio. In : http://miaumiau.cat



3.10 NURBS Curve of 2 degrees with control points, by : Interactive studio. In : http://miaumiau.cat



3.11 NURBS Surface generated in Rhinoceros.

Image

Chapter Four

Digital tools supporting performance Based Design

Digital tools supporting performance Based Design

As we have analyzed, the construction of 3D models is mainly focus on polygonal meshes, solid model or parametric models such as NURBS.
One well spread approach to create architectural models is to follow a technique in which solid modeling is created from the planar and orthogonal nature of the architectural design. This technique is called 2.5-D, which operates on the extrusion of lines or polylines to a certain distance. The popularity of free-form parametric models that work under the scope of NURBS-based surfaces is growing at a good pace. The proliferation in computer processing and the presentation of computer-aided manufacturing is influencing as well, due to the prices of manufacturing free-form architecture are not that high. Furthermore, prominent architectural schools have founded design studios whose research programs converge on the use of digital tools.

Lets categorize the types of tools we can operate with in the realm of performance-based design;

Drafting and modeling software

This group presents two kinds of software that cover most of the tools employed by designers and architects. The first kind is drafting software, this one is limited in 3-D modeling faculties and its main use is to produce 2-D plans, designs and documentation, this type of methodology is the main connection between designers and builders. The 3-D components involved in this software generally work under orthogonal modeling alternatives established on solid modeling and polygon meshes, therefore free-form design is not that creatively exploited. The most important software programs are Autocad (www.autodesk.com), Datacad (www.datacad.com), Microstation (www.bentley.com), and Vectorworks (www.vectorworks.net).

For the second category we will find the modeling software created for designing, modeling, representing and producing building components for architectural purpose. This modeling software, some times works as animation software. Among the most representative software we find 3ds Max (www.autodesk.com), SketchUp (http://www.sketchup.com) and Rhino (http://www.rhino3d.com/)……

Building information modeling

In the 1990s, architects and designers experienced a different approach to digital software. This kind of software offered a resolution for the requirements of both 3-D model-

ing and 2-D documentation. This digital tool generated, the plans and the sections from the 3-D model. This methodology is likewise called “one-model design” or “one-model building”. Even though these kind of software counts with an incredibly fast workflow the free-form design procedures have not yet been fully developed under this scheme of software, which is considered as a limitation when designers try to emphasize in formal expression. The leading software programs of this type are Architectural Desktop (ADT) (www.autodesk.com), Revit (www.autodesk.com), Archicad (www.graphisoft.com) and Microstation Triforma (www.bentley.com).
Bentley has been one of the leaders in this type of software and has developed a parametric software called Generative Components, which is able to define complex constrictions. This software creates conditions and rules after generating a general geometry of the project, so in this way it introduces an extra stage in parametric software in architecture, which is the capacity to produce and manipulate complex geometric limitations. Nevertheless, in order to relate with the program most of this software demand programming knowledge, which is becoming essential for the average architect.

Modeling software designed for other professions

When we started talking about digital architecture we pointed out that most of the modeling software used by architects during this age were initially developed for other fields like animation and mechanical-industrial design. These software programs were introduced to the architectural studios as part for modeling and representation, and to be involved in the designing methodology for exemplifying the final product. As discussed in other chapters of the thesis, the free form elements are highly noticeable by designing and manufacturing under these kind of software. The fact that these software were strictly created to supply industrial and mechanical design allows a more precise manipulation of complex forms. In addition, these programs can correspondingly export numerical data to CNC and RP machines and are able to calculate real material performances. The best exemplars of this type of digital tools are: Rhino (www.rhino3d.com);Solid Edge (www.solid-edge.com); SolidWorks (www.solidworks.com); Pro/E (www.ptc.com), Maya (www.autodesk.com), Alias Studio (www.autodesk.com); CATIA (www.3ds.com).

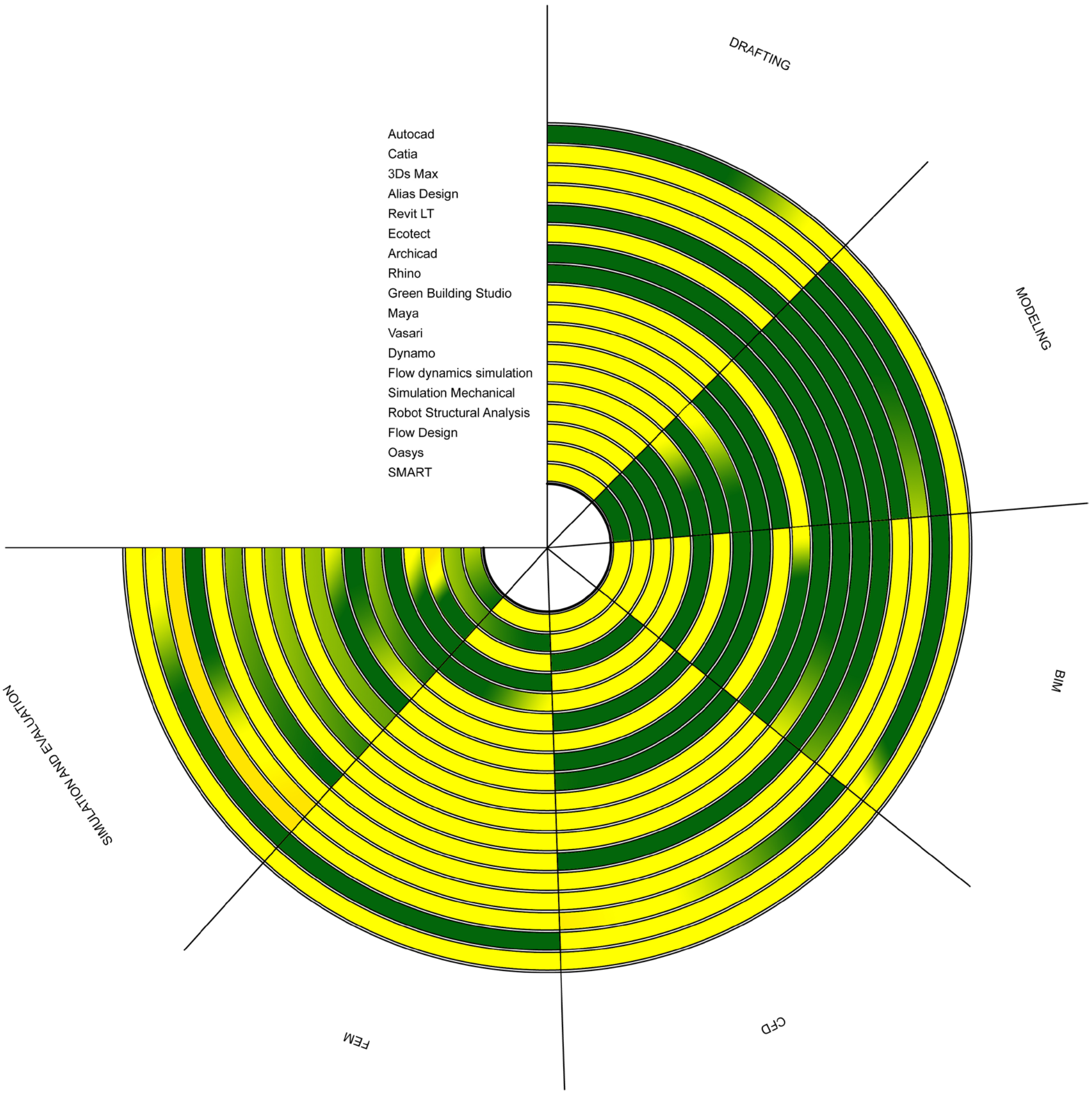
Simulation and evaluation software

On the last years this kind of software was focused on professional consultants that were in charge of evaluating the design to programmatic requirements that are related with performance factors as acoustics, wind, energy conservation and efficiency and others. In order to be more precise we can distinguish two main methodologies of operation for computer-based design: the generation of form (morphogenesis) and the form optimization. In the next chapter I'm going to deliberate about the design optimization and how can be defined in this context as a pioneer in the manipulation process for achieving certain performance criteria in the project. Lets make a division of the different process involved in simulation software, they are separated in three processes; *simulation, evaluation and modification*. In the simulation stage the goal is to imitate real conditions by using mathematical models that exemplify the comportment of an object from a singular performance point of view or the interaction between several performances. The evaluation phase focuses on determining differences between accomplished and expected established performances.

The last phase of these three is the modification, it is where all the previous ones summarize; modification is concern in creating a strategy that concentrates in the adjustments that need to be performed so the design can decrease these differentiations and the actual execution of these changes. In this chapter of the thesis, the meaning of generation in terms of design; could refer either to the process of developing from a certain base point or to the process of creating a design from scratch. As we know most of the generative methodologies do not stop after the initial form has been generated but there is a continuous enhancement of it. In order to prove these two theories, the thesis will focus on studying these two possibilities; generation and optimization.

Computer based optimization

As we have noticed, the relation between computers and software is growing side by side into a global connectivity necessary for architects. What's more, the standardization of protocols is making possible to import and export data generated by different software to have a cohesive evaluation of the different areas involved in a project. As we know, in the field of architectural design the appearance of this software was mainly at the end of the project, this notion is changing and the role of simulation in architectural design is being used during the different phases of the design process including different disciplines that make part of a building project. The argument here relies in the fact that design is becoming more involved into parametric software; the 3D models are being used by simulation and architectural software. The approach that we are going to follow is to discuss the role of computer-based simulation software used by architects. In addition, there is an importance to clarify the general state of simulation software and the methodologies employees by consultants and designers.The computer simulation has been used for a long time in architectural studios, mainly as a representational media, involving renderings and animations for commercial purposes. On the other hand, this type of simulations permits to analyze in a performative point of view the mainly qualitative aspects, such as esthetics and implantation into the place architects work in. However, the quantitative aspects focused on particular issues as simulating light/shade conditions. A second category of performance-based simulation employed by architects engages physical forces modules from animation software, like Maya or 3ds Max. The conception of this software relies on the fact that was created for the entertainment industry; they emphasize more on the effects than in the physical accuracy of the simulation. Consequently, this approach into performance-based optimization becomes very superficial and the use of these models is concentrated in a creative form-based design.



4.1 Taxonomy of digital software Tools

The thesis will go deeper in understanding the simulation software that was created for other disciplines and is becoming a fundamental tool in the creative process for architects, lets have a look to its evolution. We can identify four clear stages;

First stage

It was marked for having a guide oriented computer applications to ensure the user of it with the decisions of building performance criteria.

Second stage

Around 1975, a deep study focused on imitate real physical conditions in a building, most of the dynamics explored in a building couldn't been fully exploited due to the processing power of the computers an the limitation on its interfaces.

Third stage

The progress in the 1980s was important, but most of the variables were attached one to the other, only time and space were independent parameters under the scope of this simulation software. This avoided the isolation of the parameters and no single energy or mass transfer could be calculated in independently.

Fourth stage

This fourth stage is a continuous development from the mid of the 1990s until today, this developments have changed dramatically the way we approached to simulation software, due to the advancements in user interface and data modeling. One of the particularities in the fourth stage is of making explicit as possible the built-in assumptions, understanding that these ones are going to guide the variant analysis in order to be of a clear interpretation. The demand for simulation software is increasing; even though the supply is quite extensive. For instance, the U.S. Department of Energy organized 335 different software programs aimed at simulation of energy performance alone. As explained before the simulation tools are clearly categorized in; sun shading and lighting, construction, wind, acoustics and energy.

Evaluating all the software available for architectural purposes will be not feasible; instead I will choose the most representative programs of each category in relation with the suitability for the architecture field.

Sun shading and lighting

This is one of the most common field of concentration by digital simulation software, it can be categorized as follows:

1. Quality of light and intensity; this division is in charge of calculating daylight and artificial lighting employed in a building, these ones embrace punctual photometric calculation in every segments of the project design mixing the use between artificial and natural manners of illuminating.

2. Geometry of shading and intensity; the shading conditions is calculated in different time frames and the calculation of shading factors. After analyzing several 3D software, it was easy to recognize that most of them offer shading-lighting simulation elements. In addition, some of them calculate photometric calculation components for shading, lighting and daylight. Usually these types of software represent the calculations as an image condition of the light-shade relation in the project, avoiding the numeric information involved in the illumination of the modeled project.

In the case of software as Autocad, Rhino and Revit ; they offered a first approach into geometric calculations of shading conditions, but not a deeper understanding of lighting components. This is one of the main reasons why academics and professional consultants dominated the usage of sunlight-shadow calculations. During the last few years, we have had enormous interest from designers to calculate and visualize this data in early stages. Now days, we can find developers focused on designing plugins for the main modeling software.

Following we will find several examples of software that was considered exclusive and out of reach from commercial architectural software:

ECOTECT; was developed by Square One Company , this software offers numeric data of illumination levels in any point of a 3D model. The data is shown in different types of numerical grid, contoured in 2-D and 3-D lux and DF (Daylight Factors) images.

SUSTARC – generates solar rights envelope (SRE) and solar catch envelope (SCE) – the volume of possible solutions that consider either solar insolation or solar shading.

SCE – presents the lowest possible locus of windows and possible solar systems on the building under consideration so that they are not shaded by existing neighboring buildings during a given period of the year (generally winter). The user interface and example of an output is presented in Figure 64 (Capeluto and Shaviv, 1997).

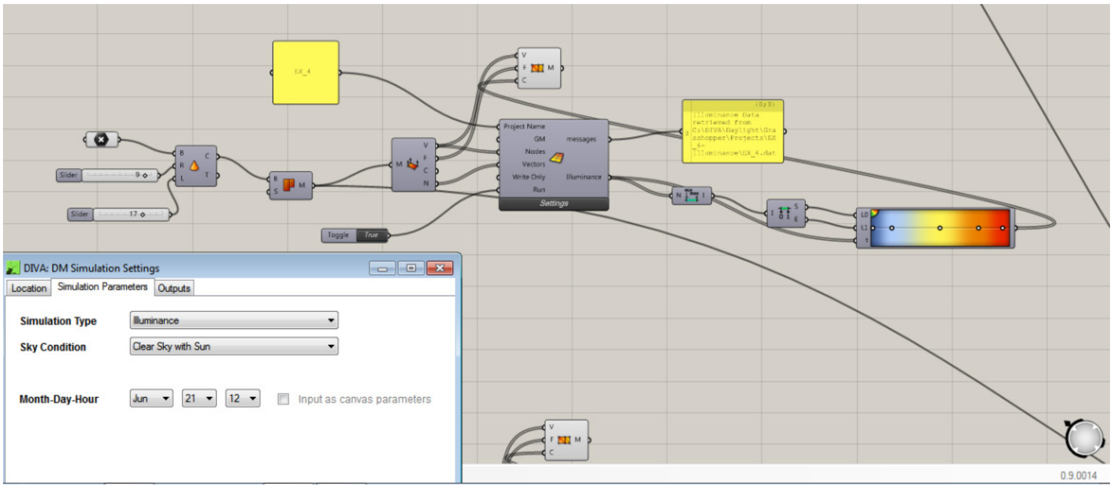
SHADING – this application calculates numeric data on local shade conditions for specific open spaces, roofs, facades, windows or any other selected surfaces in a predefined time frame (year, month, hour of day). The user interface with an example of an output is presented in Figure 20 (Yezioro and Shaviv, 1994).

SRE – calculates the maximum height of a building which doesn’t interfere with the solar rights of the neighbouring buildings taking into account diferent periods of the year.

RADIANCE - Suite of programs for the analysis and visualization of lighting in design developed by Greg Ward Larsonat Lawrence in Berkeley National Laboratory (1985 - 1997).

It calculates values of spectral radiance (ie. luminance + color), irradiance (illuminance + color) and glare indices. Simulation results can be displayed as color images, numerical values and contour plots.

Experiment: RHINO+GRASSHOPPER+DIVA(plugin)



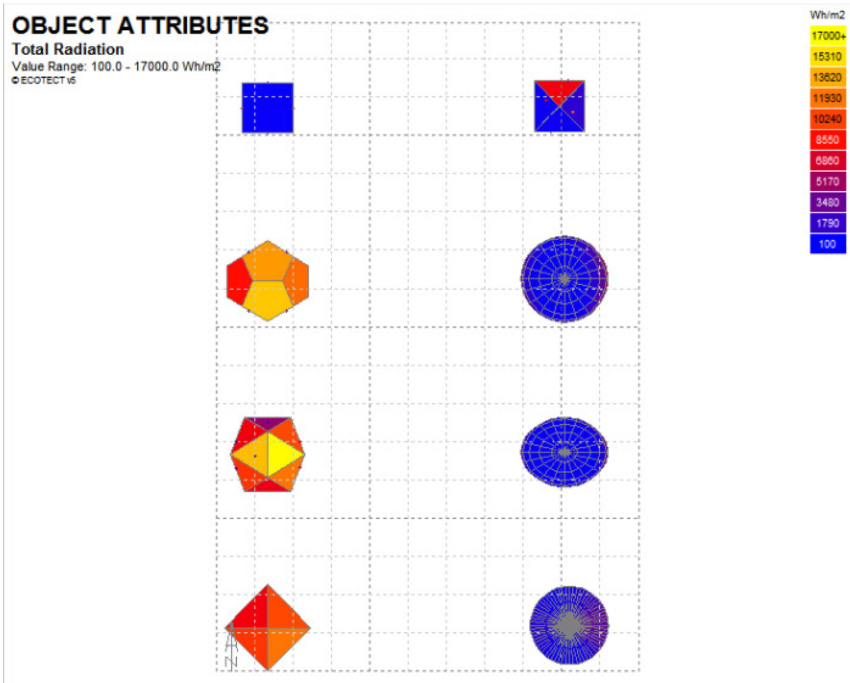
4.2 Environmental performance evaluation in Rhinoceros

4.3 Cube & dodecahedron radiance results

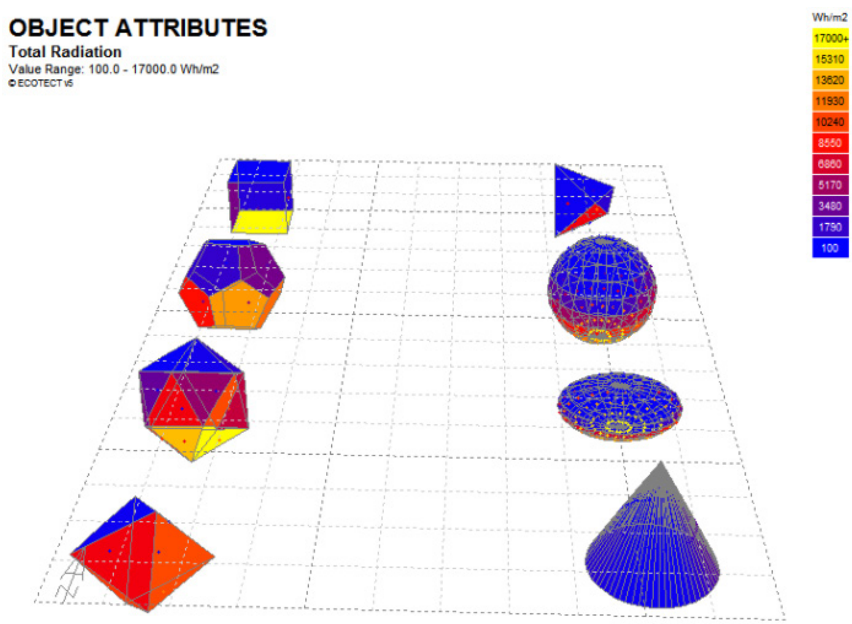
4.4 Tetrahedron & sphere radiance maps over surface

4.5 Ellipsoid & Cone radiance mapping

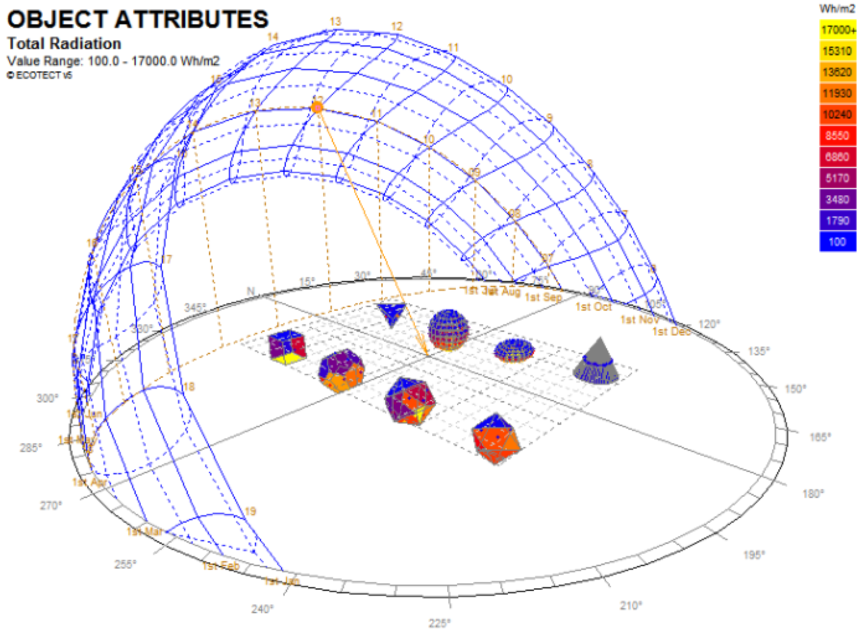
4.6 Icosahedron & Octahedron radiance divisions over falt surfaces.



4.7 Group radiance mapping over solids



4.8 Radiation values-Perspective



4.9 Direction of the radiation over solids

Structure – loads, stress simulation

The development of structural software has been available for a long time. Finite Element Calculation open widely the exploration of this field, so designers could manipulate a 3D based digital simulation of the structure. Making a general overview; will show Finite Element calculations are in charge of dividing the general structure so the load for every element can be calculated, as next step the results are regrouped to have a complete notion of the loads involve in the design. The Finite Element 3-D model simplifies the entire building model inspection, analyzing the common influences of diverse components in terms of resistance to loads. This kind of approach in architecture brought a substantial improvement due to it was then possible to reduce the quantity of material used to resist load forces and to be highly precise in calculations.

The position of FEM structural software is an antagonist one with respect of the commercial CFD uses of wind simulation software. Structural software have not been well spread among architects in a deeper way, their main outputs focuses on representing information relating numerical, dynamic and statically visual loads or stresses of the project. What's more, their use is segregated from popular 3D model software. Consequently, form and structure have been treated as separate procedures in architectural design due to several reasons:

1. FEM structural tools are complicated in the way they operate, most of the architects need proper training in order to operate with them.
2. Most of the architectonical modeling software has no direct relation with FEM structural software, this leads to remodeling the project in the correct program, which is time consuming and interposes in the usual process of design.
3. The role of the structural engineer in a project has been always of presenting a simulation to the architect. Therefore, architects avoid spending time in this type of labor because they are not enough motivated, even though we should considered the motivations behind understanding the capabilities of this software;

    - Late developments of complex forms, intricate geometry and program issues in a project adapt to the software interface, in this way is easier to recognize preliminary structural calculations so it becomes an advantage for architects in avoiding problematic design directions.
    - As the digital architectonical industry is shifting into managing one –model design, the distances between design and structural simulation are decreasing.

Wind Simulation

To describe wind simulations we have to take into account three main types of considerations that must be adopted by architects throughout the design process. If we analyze the urban scale the main goal for the wind is to avoid places where the wind studies show that people will have difficulties to stay or feel comfortable, otherwise, the methodology is make them experience desirable winds, consequently natural ventilation could be a good option. On a building scale, it has to be contemplated for two purposes, one is internal ventilation and the other one is taking in account structural stability of the building and its relation with lateral forces generated by the wind. The simulation of the collision of the wind on the buildings volume could be compared to a dynamic load-stress simulation that has a strong relation with the manner simulation processes are computed with the structural software.

On an urban scale, Computer wind-flow tools that replicate wind have been employed and improved since the 1990s. However, this kind of software has been designed to work as an external tool from the modeling software, lets take a look into some of its characteristics;

1. As the structural software, wind simulation tools are complex, but in the last decade they have become strongly popular in avant-garde architectural studios.
2. The architectural 3D model designed for representational purposes, in most of the cases can't be exported directly into wind simulation software.
3. As mentioned before, one of the main reasons for performing wind simulations is to examine the influence of wind in relation with the building's structure, as well as to examine the influence of wellbeing, for instance; pedestrians and people that go out to balconies and ventilation by the use of windows in the project. In the case of Structure-related wind simulation, its crucial in certain types of building, such as; high rise ones, bridges and prominent structures.
4. About comfort and ventilation, these kind of perform simulations is reserved for mega structures or expensive buildings in order to assure environmental certainties.

Now lets discuss the main architectural motivations for the manipulation of wind simulation software

1. The fact that wind simulation can envisage structural problems in the design of the building projects can help the architects into take a correct posture for modifying certain parameters of the project.
2. For energy consumption reasons, the correct use of natural ventilation can reduce dramatically the energy supply, so buildings control the use of cooling and heating systems.
3. When the wind simulations can establish comfort zones in the architectural project, designers can take advantage of this situations and increase usable space and fine-tune spaces to increase human comfort, thus also saving energy.
4. The fact that architecture is being more permeated by 3D parametric modeling is closing the gap between design and wind simulation software.

Acoustics Simulation

This simulation, as the one before, has two main scales; an interior and an urban scale (exterior). For the exterior, acoustic simulations could influence in the organization of the buildings on a specific location and the necessity for planning acoustic barriers. The building scale (interior), influence in several areas of the acoustic simulations and architectural designs, including conference rooms, music halls between others. The geometry and the materials of a project is as well influenced by the acoustic simulations. As the other simulation software, the acoustic tools are developed outside of the commercial architectural software. This can be explained by the complexity of the software and the fact of needing to rebuild the 3D model as in previous examples. For the urban scale, the simulation helps urban planners to take a stand relating to the future land use and the possible location of neighborhood areas. In addition to this, the studies help to define new types of materials involved in the architectural construction and to decrease the high levels of noise in conformed urban environments.

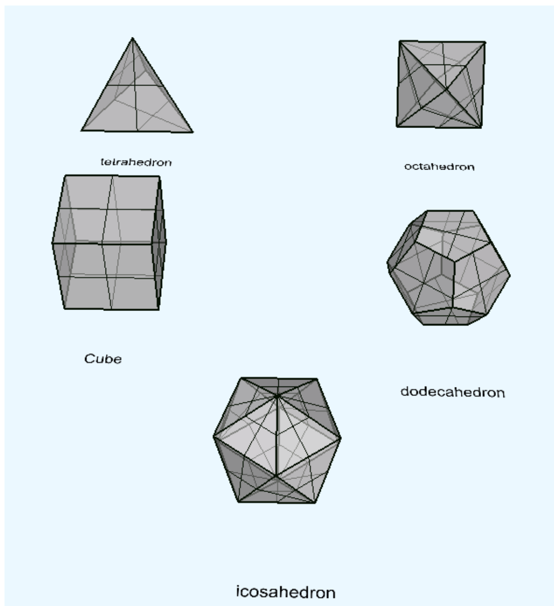
For the interior design in building projects the use of the software in early stages defines which type of materials could be used and the general geometrical design, avoiding mistakes and problematic design directions. It becomes a huge help for defining and improving the acoustic performance by using the acoustic digital consultant for finding the correct tuning.

Wind simulation in Established Geometrical models

Under the scope of analyzing wind simulation criteria through digital tools, the first approach was guided by recognizing the most influent geometrical models in architectural geometry. The focus of this part of the thesis relies on finding the advantages and disadvantages of the formerly established geometrical figures when the simulation processes start.

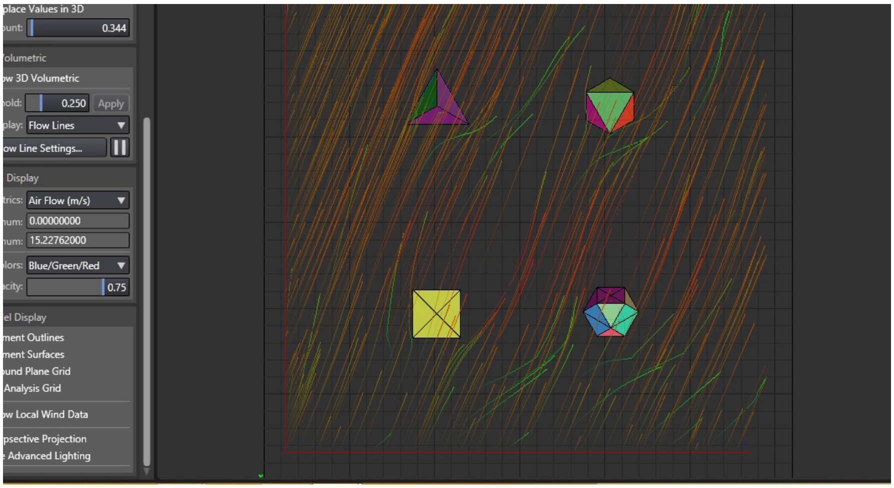
The study will do an overall lecture of the surfaces, identifying essential formal characteristics

Platonic Solids

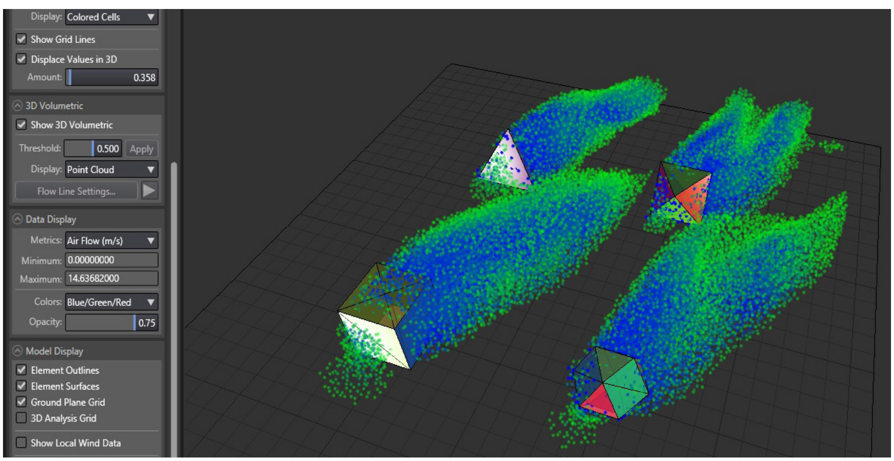


4.10 Platonic Solids

A platonic solid is considered a convex polyhedron if all of its faces are congruent regular polygons and at each vertex, there is the same number of faces meting. In this last case three is the minimum number of edges and polygons that must encounter in the vertex. It is considered for a polyhedron vertex to be convex if summing the consecutive angles of the edges is less than 360 degrees. Therefore, in the case of the cube if we sum up the three faces meeting at each vertex 3.90=270 degrees. Three equilateral triangles; 3.60=180 degrees, in the case we add another face get the tetrahedron we will encounter the tetrahedron, which satisfies the characteristics described above making it a platonic solid. The octahedron is formed by four equilateral triangles 4.60=240, and joining them together at the base. The limit of equilateral triangles we can get meeting in a corner will be five,5.60=300 ;icosahedron. In this case we can't join two vertex pyramids in their pentagonal bases, but to make use of 5 equilateral triangles at the bottom and at the top of the figure. Now lets take a regular planar polygon as the regular pentagon, it has 5 edges and an inner angle of 108 degrees; 3.108=324. The dodecahedron is obtained by joining these 3 groups of pentagons.



4.11 Flows over; cube, octahedron, tetrahedron & icosahedron a top view

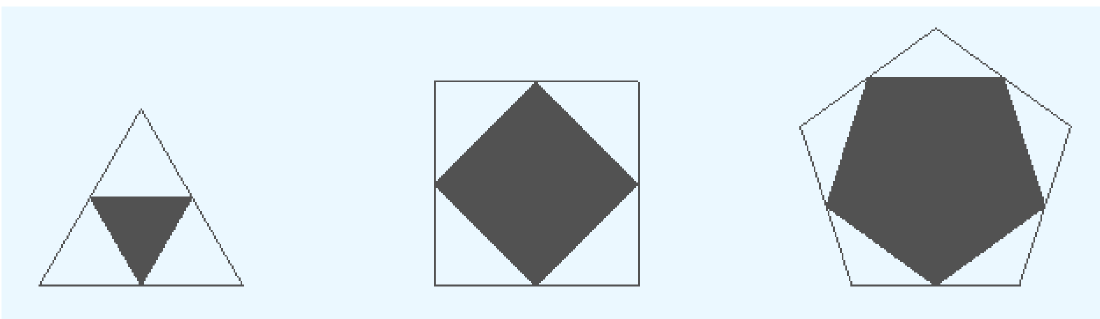


4.12 Perspective wind analysis over figures.

Archimedean Solids

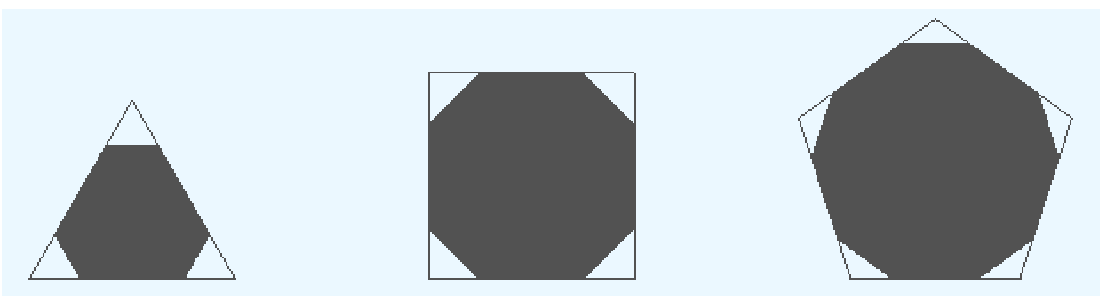
These solids are considered convex polyhedral made of two or more types of regular polygons; therefore all vertex pyramids become congruent. They share a common characteristic with the platonic solids, is that all edge lengths are equal. On the other hand, a strong difference is that they appear more than one type of planar faces.so, the faces have to be regular polygons, but not all of these must be congruent. Cutting off the vertices of a platonic solid makes the generation of some Archimedean solids. Lets take a look to the types of cuttings we can do, we can perform two diferent types of cuttings in order to arrive to a regular polygon. In the first case the cut will happen in the edge midpoints, the second type the cut is done so the new polygon has as twice as many edges becomes rregular.

Cuts type 1



4.13 First type of cutting

Cuts type 2

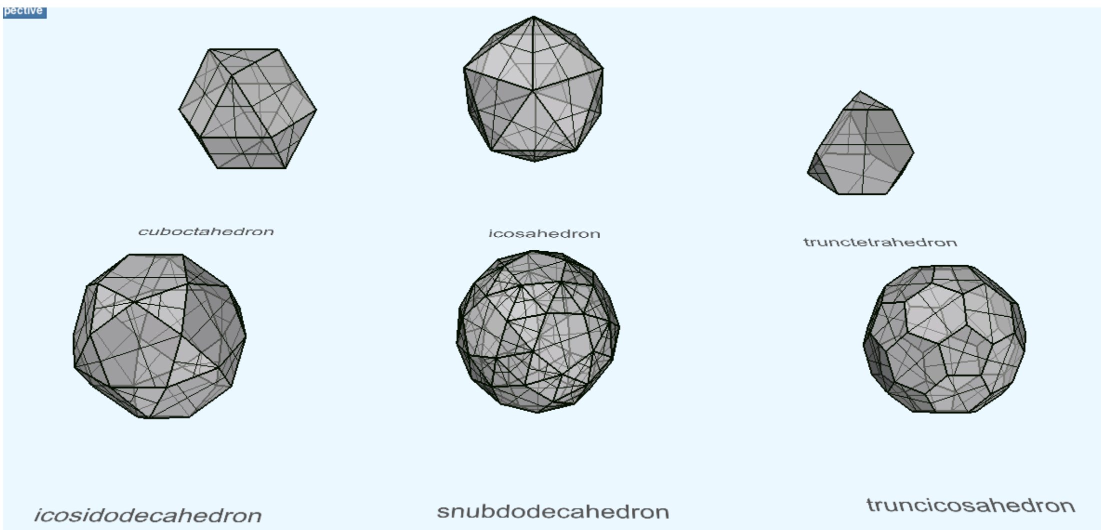


4.14 Second type of cutting

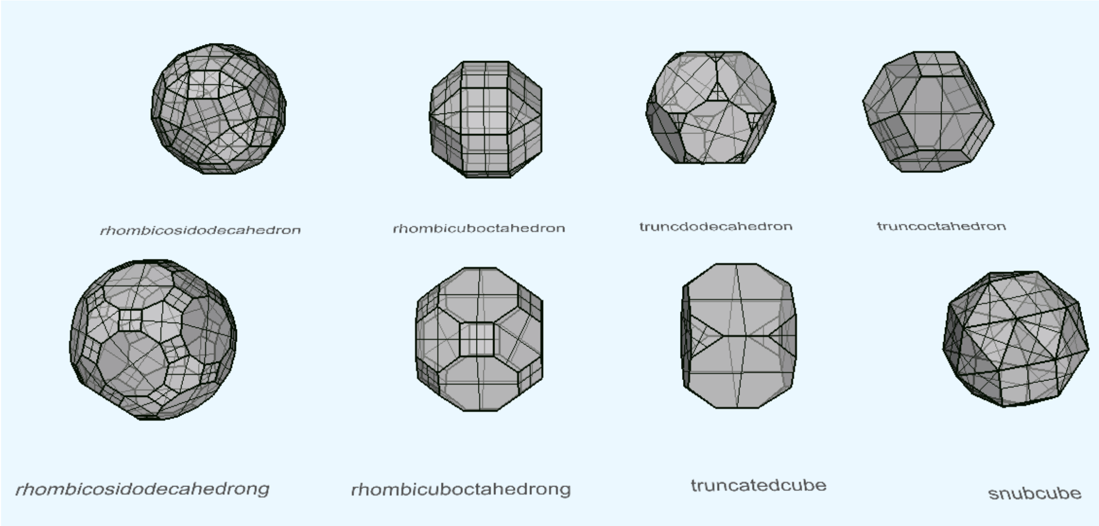
Corner cuts type 1

In the case of a Tetrahedron we can cut off 4 small tetrahedral then the result is an octahedron, arriving at a platonic solid again. The cube can be chopped in its corners as well, obtaining a cuboctahedron; its made of 6 congruent squares and 8 congruent triangles.

Lets take for instance the octahedron; we will arrive to the same result described for the cube. If we Corner cut through the edge midpoints dual platonic solids generate the same polyhedron. This process is repeated as well in the case of dodecahedron and its dual the icosahedron. Lets take the dodecahedron for instance and planar cut it by its edge midpoints, the result will be 20 congruent equilateral triangles and 12 congruent regular pentagons, this figures name is icosidodecahedron, by its name we can figure out that we can arrive at it as well by corner cutting through mid edge midpoints of a icosahedron.



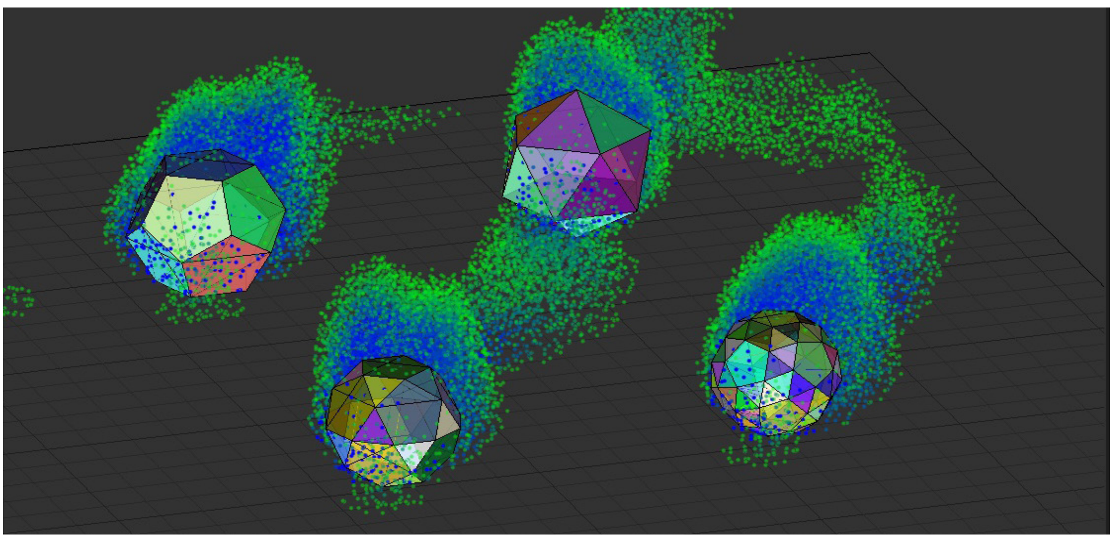
4.15 Descendants coming from type 1 cutting

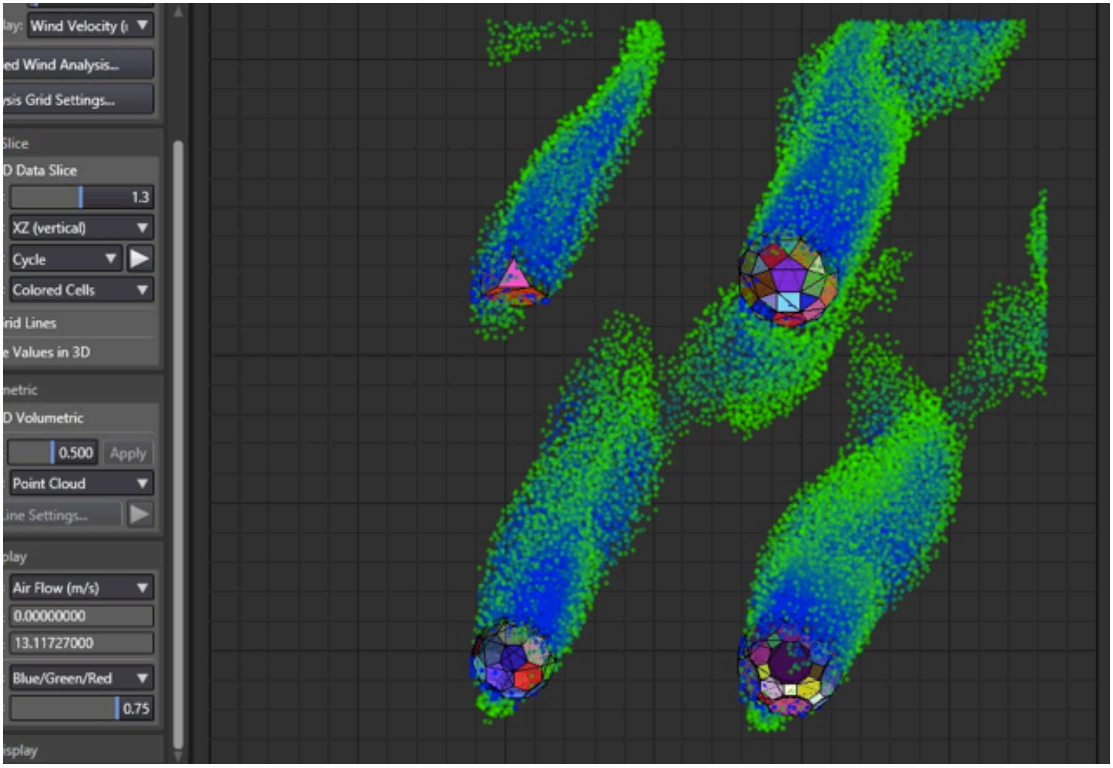


4.16 Solids derivated from corner Cutting

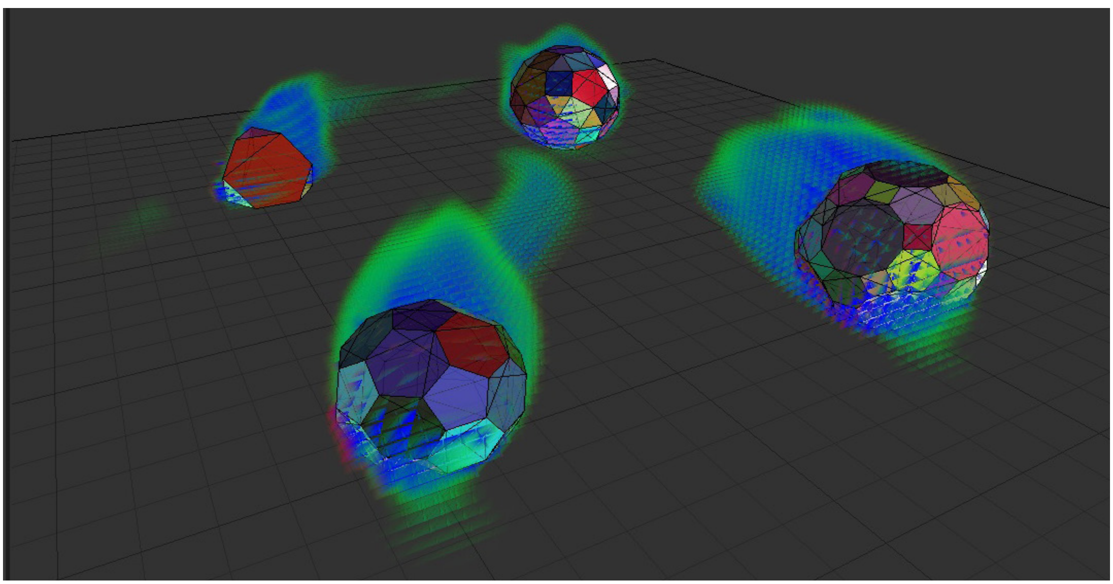
Corner cuts type 2

Applying corner cutting of the second type, will lead us to have one further Archimedean solid for every of the five platonic solids. These kind of solids generated by a process called truncation are named; truncated tetrahedron, truncated cube, truncated dodecahedron, truncated octahedron and truncatedicosahedron. Corner cutting becomes essential in the generation of new shapes from existing ones. Summing up there are 13 different Archimedean solids.

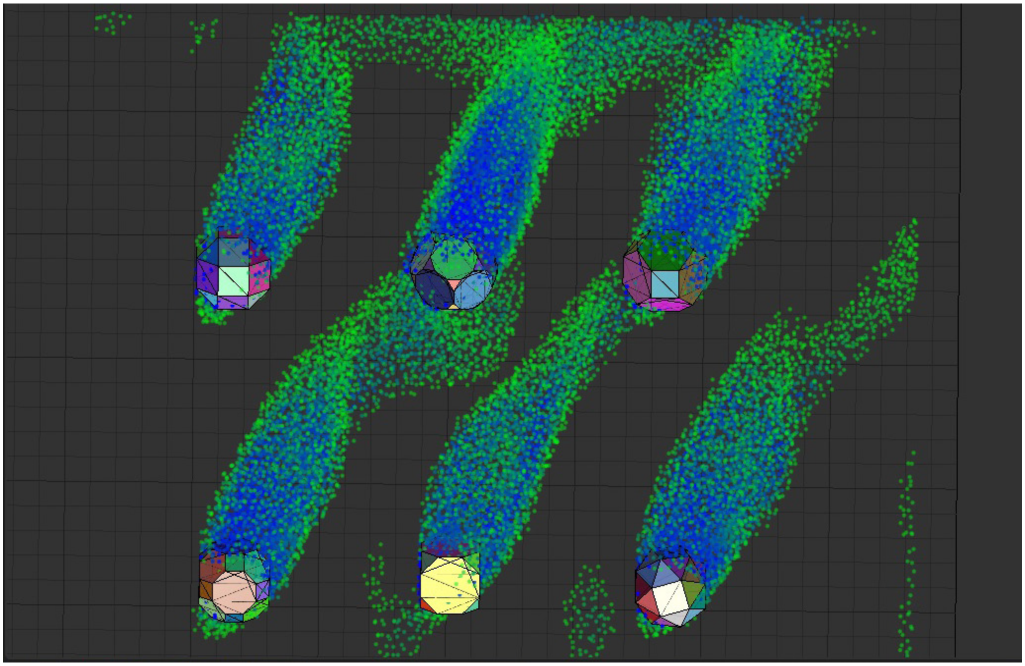

4.17 Perspective Wind Analysis



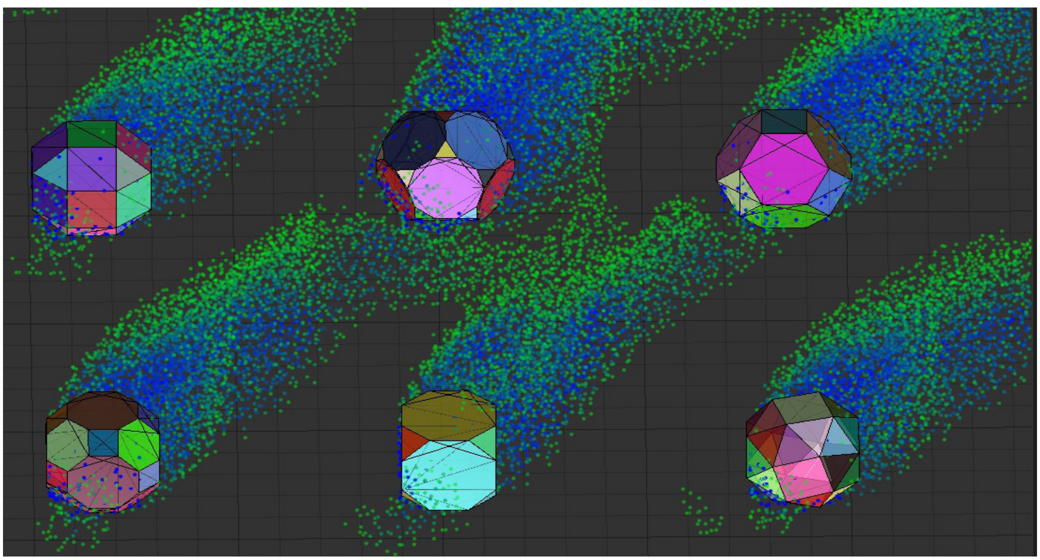
4.18 Top view Wind Analysis



4.19 Layer wind Analysis



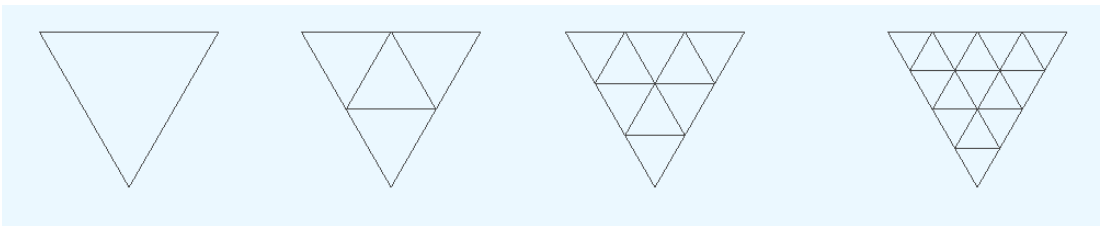
4.20 Second Group Top view Wind Analysis



4.21 Particles view Wind Analysis

Geodesic Spheres

A geometric sphere is defined as a polyhedron with the most closest to a spherical structure, as important characteristics to take into account are the fact that all vertices lie on a common sphere and some of the vertices are arranged on great circles of this sphere. The name geodesic, come from the shortest paths that connect two distinct points on a sphere. The geodesic sphere is made out of triangular faces that now days are commonly used in architecture. The process for arriving to a geodesic sphere relies on a subdivision process that divides each face in a pattern of triangles, then the vertices are projected onto the sphere.

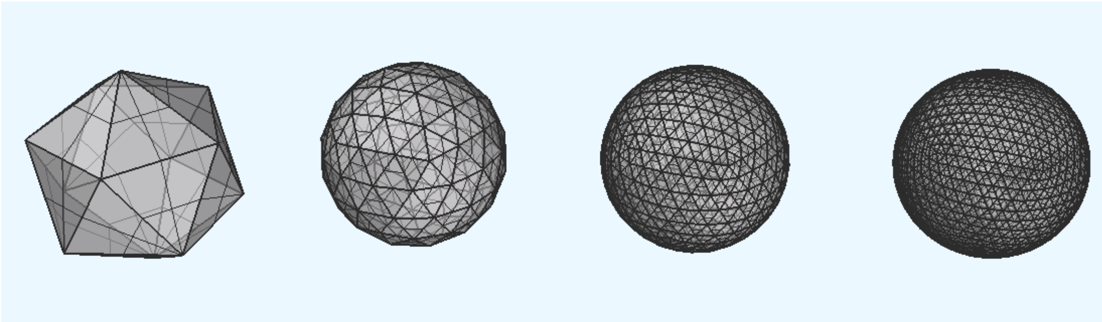


4.22 Triangle Sub-division

Type 1- Geodesic domes coming from an Icosahedron;

The use of the icosahedron is well fitted as a starting point for deriving geodesic spheres, as described before we start by subdividing the triangular faces in even smaller triangles. We repeat this process for the 20 congruent faces of the icosahedron, obtaining a total of 80 = 20.4 triangles. These new vertices (30) are projected form the center of the icosahedron on its sphere. Therefore, we will find that this geodesic sphere is made out of two different types of triangles; 20 of them are equilateral and 60 are isosceles.

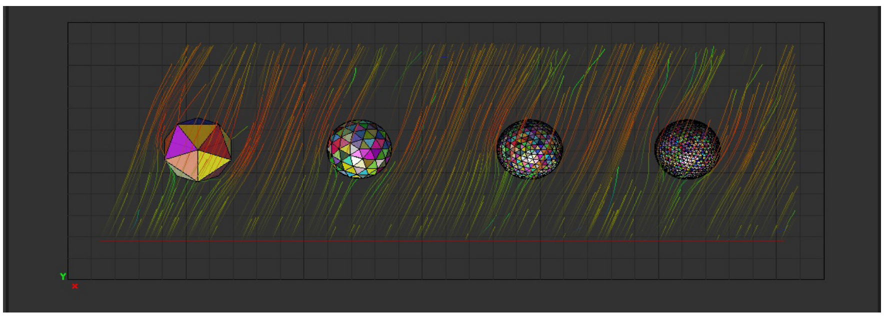
Now if we want to continue and construct a larger geodesic sphere we could; by subdividing each edge of the icosahedron into three equal parts so we obtain 9 smaller triangles from each triangle, the projection process into the sphere will be the same as described previously. In this case all of the triangles are isosceles. Still, as before we have to classes of triangles; 60 congruent ones that build the vertex piramids around the 12 vertices that were from the beginning in the icosahedron and other 120 congruent triangles. If we apply the sequent subdivision, we will find that the each triangle will be subdivided into 16 triangles.



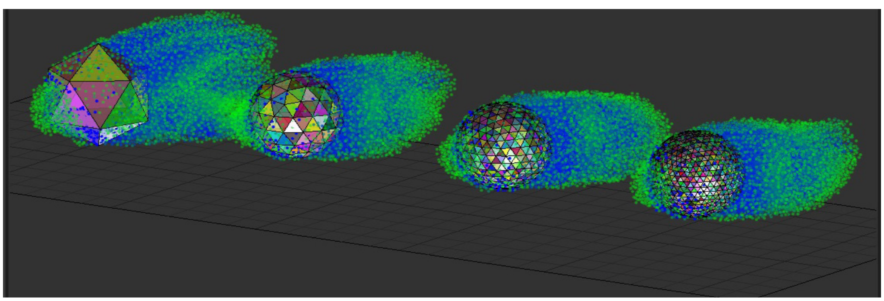
4.23 Geodesic Domes Evolution

Geodesic domes coming from an Icosahedron

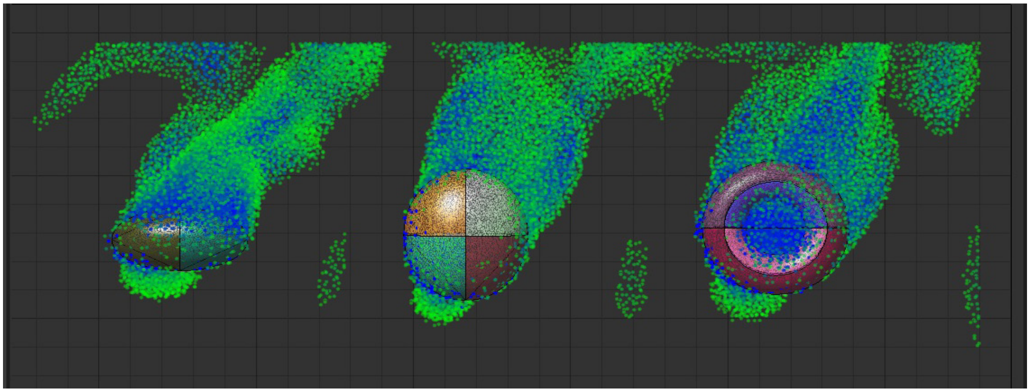
This alternative as well has as starting point the icosahedron , the difference lies after doing the subdivision of first level where we find 4 smaller triangles. After this point the order in which we perform the subdivisions and projection steps varies giving radically different results.



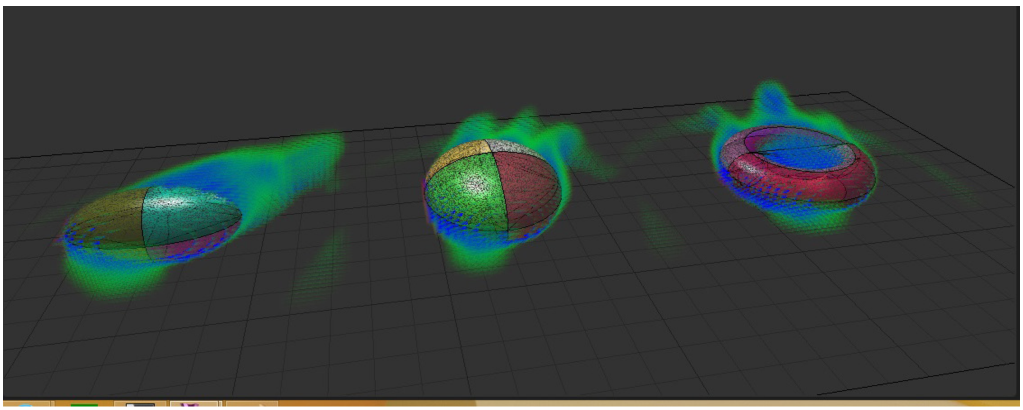
4.24 Geodesic Domes top view wind analysis



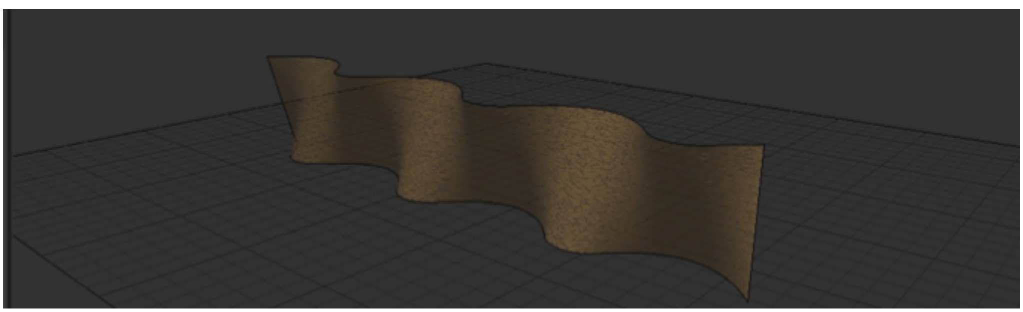
4.25 Geodesic Domes Particle wind analysis



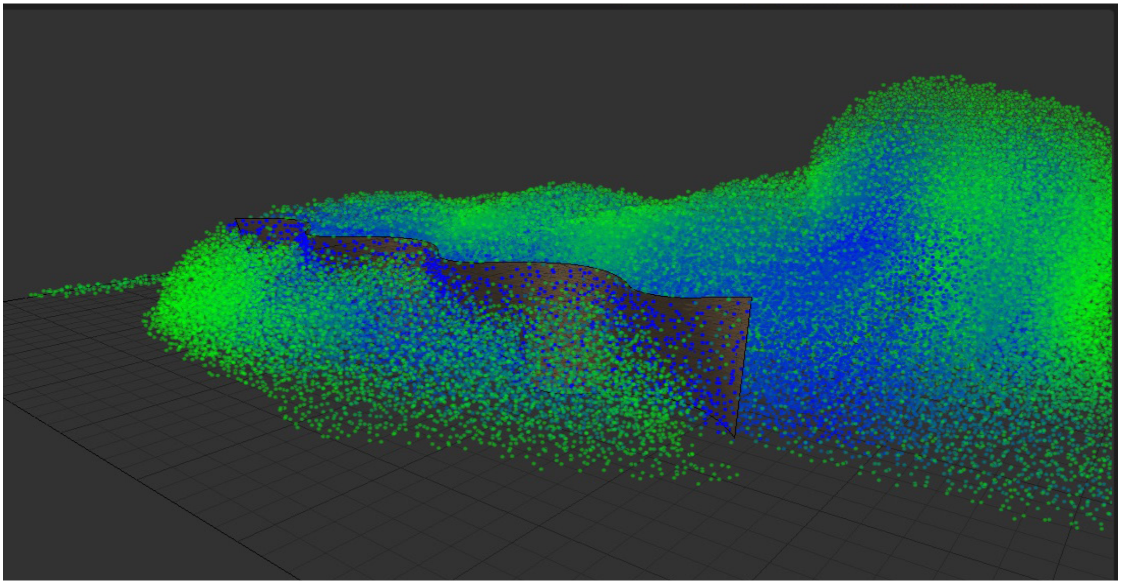
4.26 Deformed Ellipsoids & torus under wind analysis



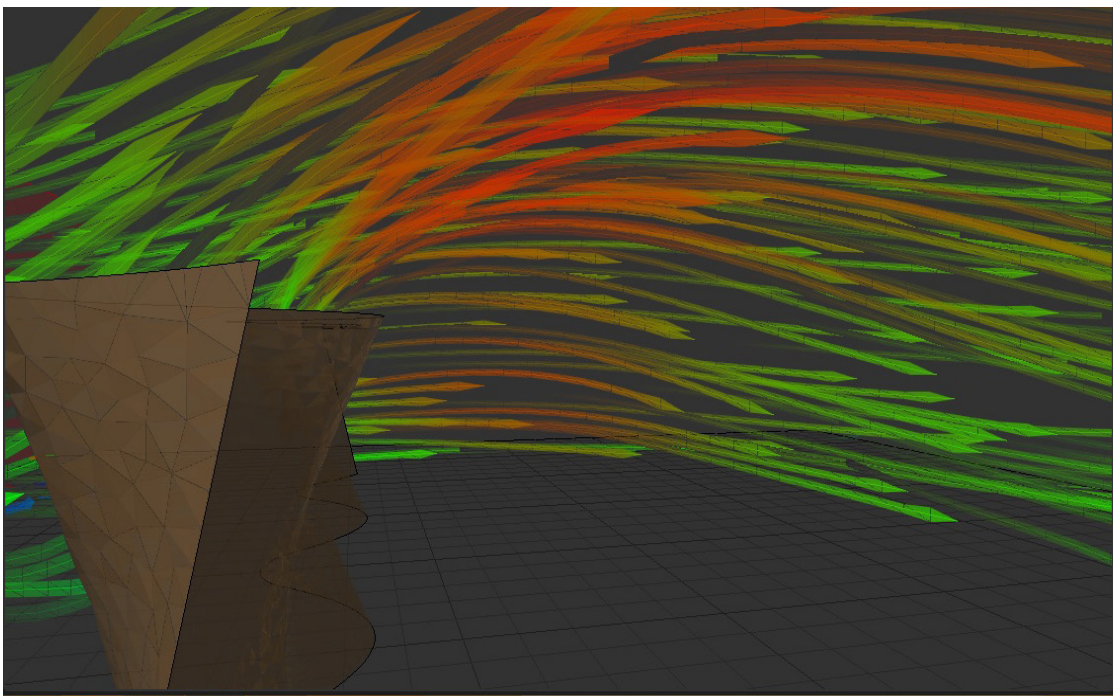
4.27 Deformed Ellipsoids & torus layer wind analysis



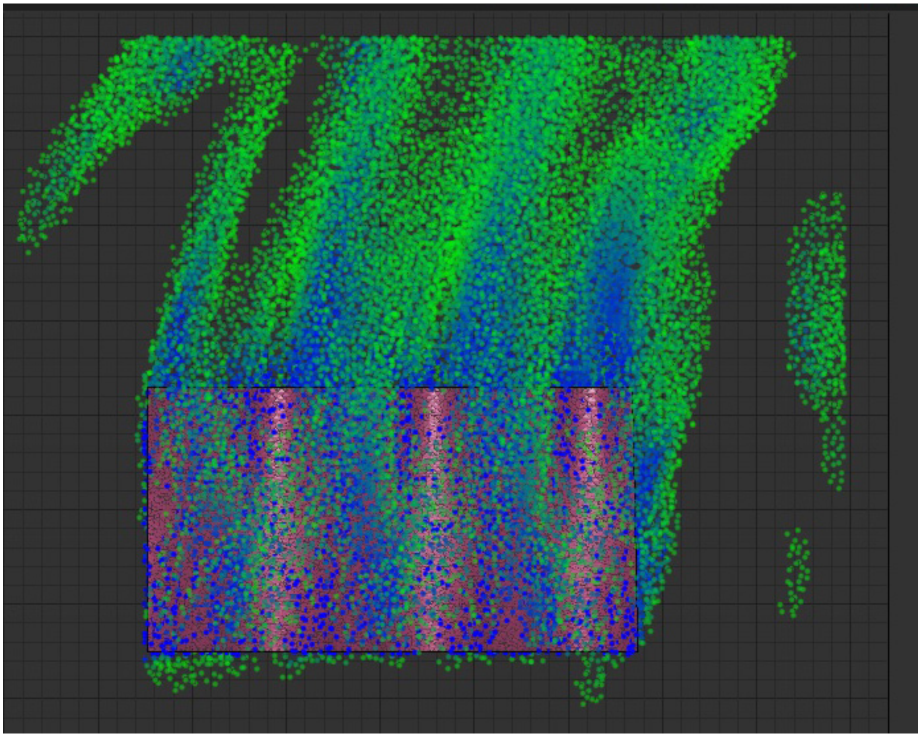
4.28 Ruled Surface



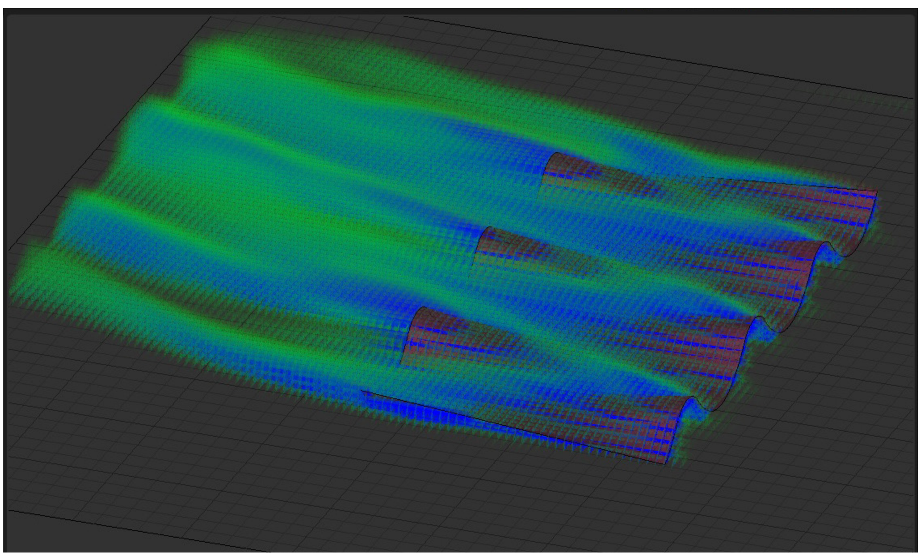
4.29 Ruled Surface Particle Wind Analysis



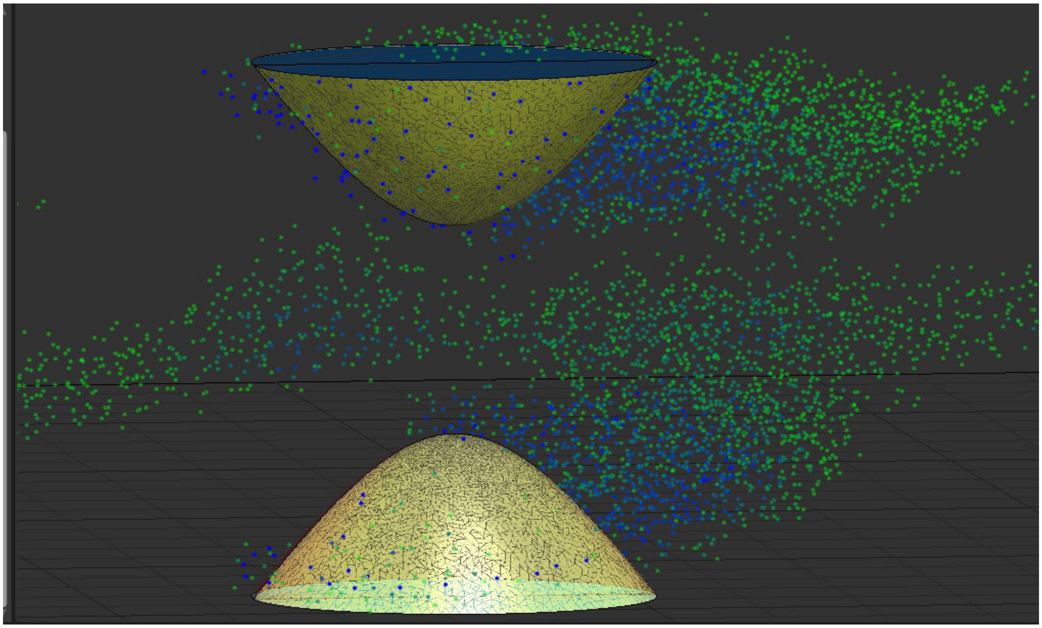
4.30 Analysis of flows Under diference Of Curvature Analysis



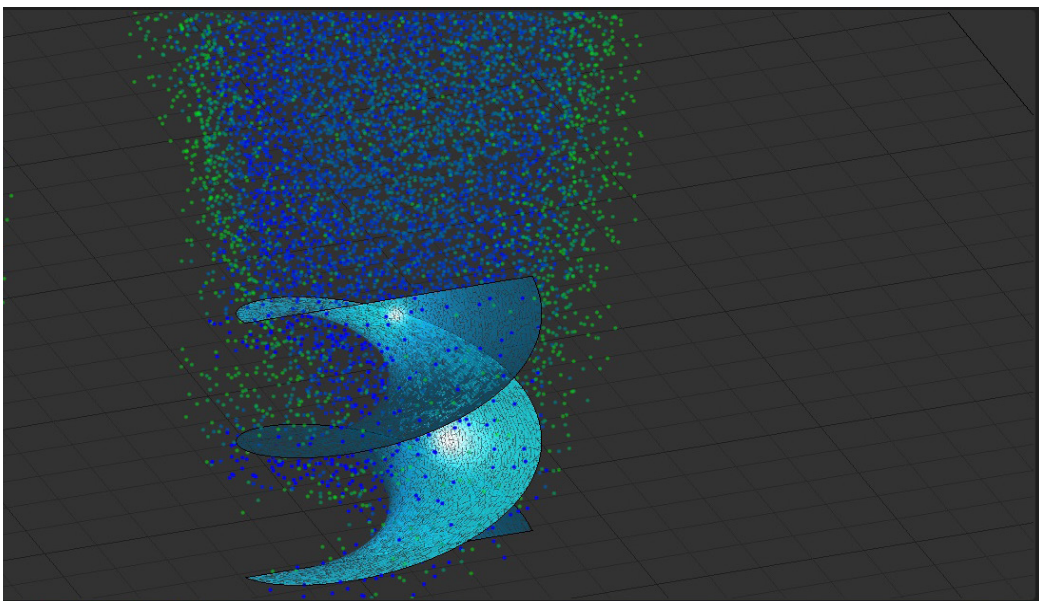
4.31 Horizontal Behaviour of Ruled Surface



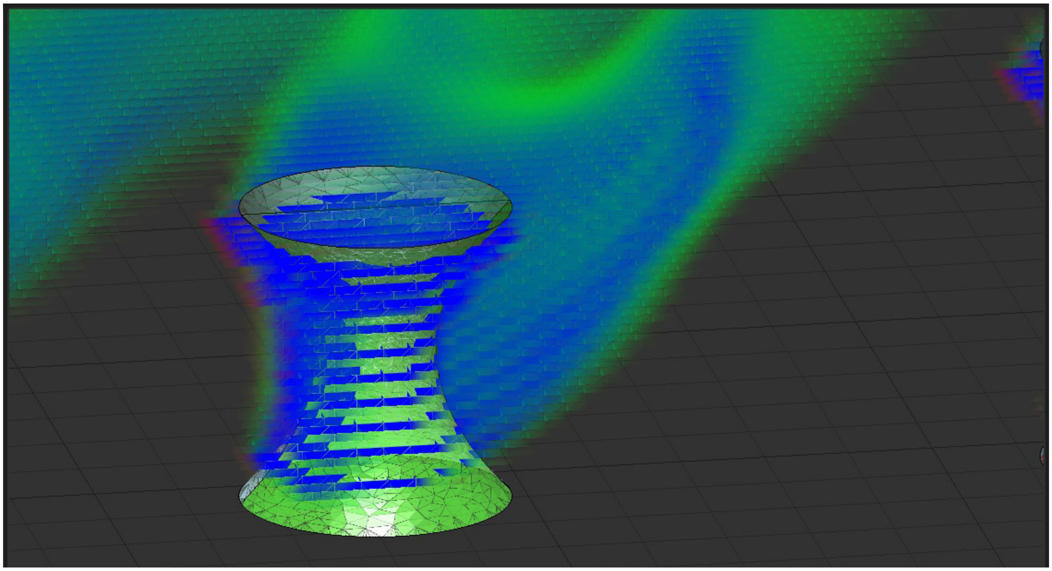
4.32 Layer Horizontal wind Analysis Under Ruled Surface



4.33 Particles passing by a Paraboloid Revolution



4.34 Behaviour of wind Particles Surrounding Spiral Surface

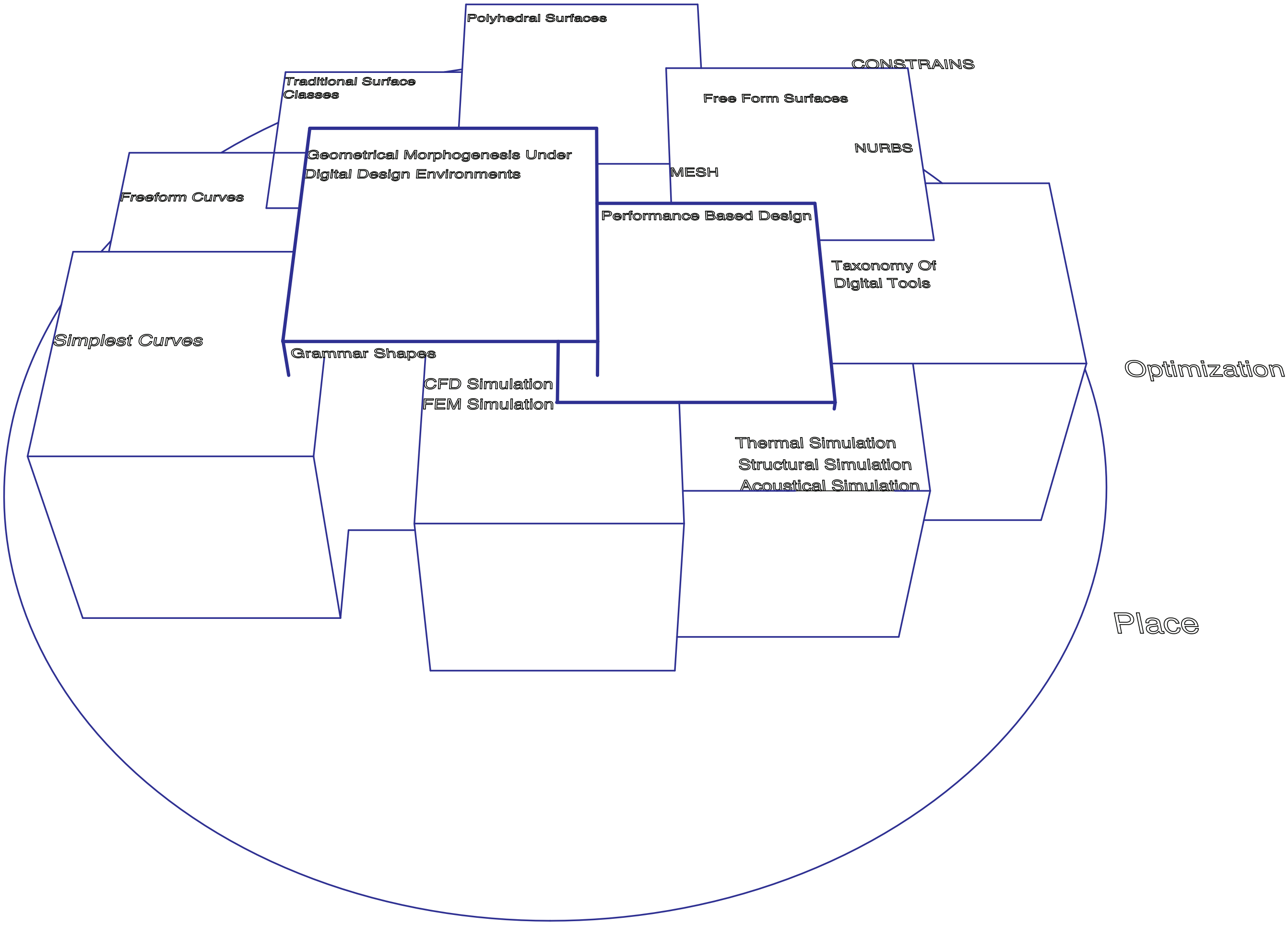


4.35 Hyperboloid of Revolution under wind layer Analysis

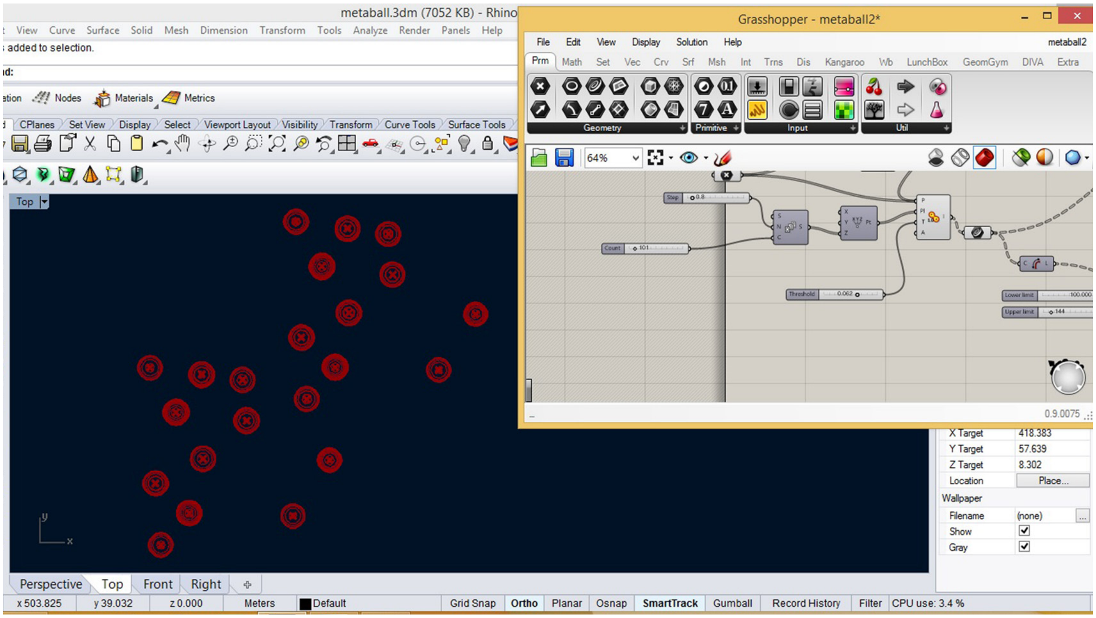
Images

Chapter Five

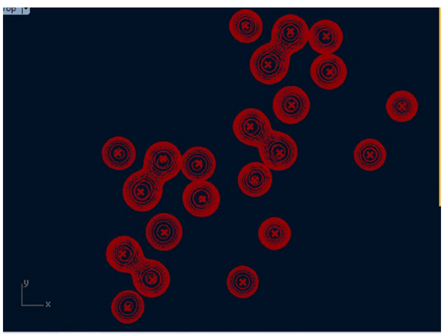
Greg Lynn As A Case Study

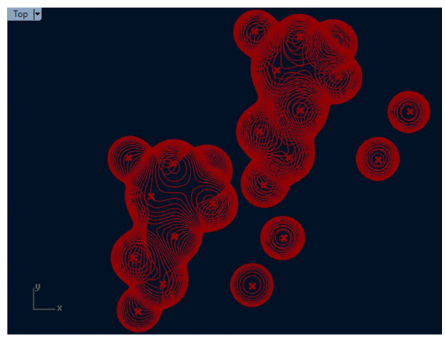


5.1 Contextual Thesis Diagram

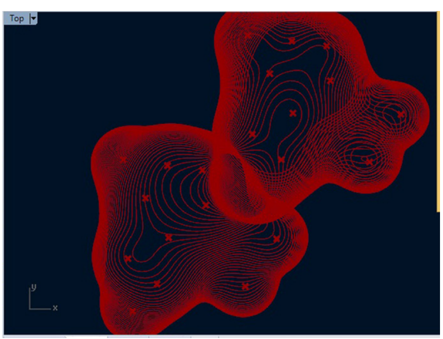


5.2 Metaball Definition-Grasshopper-

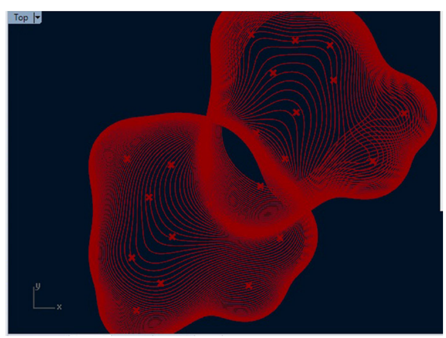

5.3 Metaball morhing



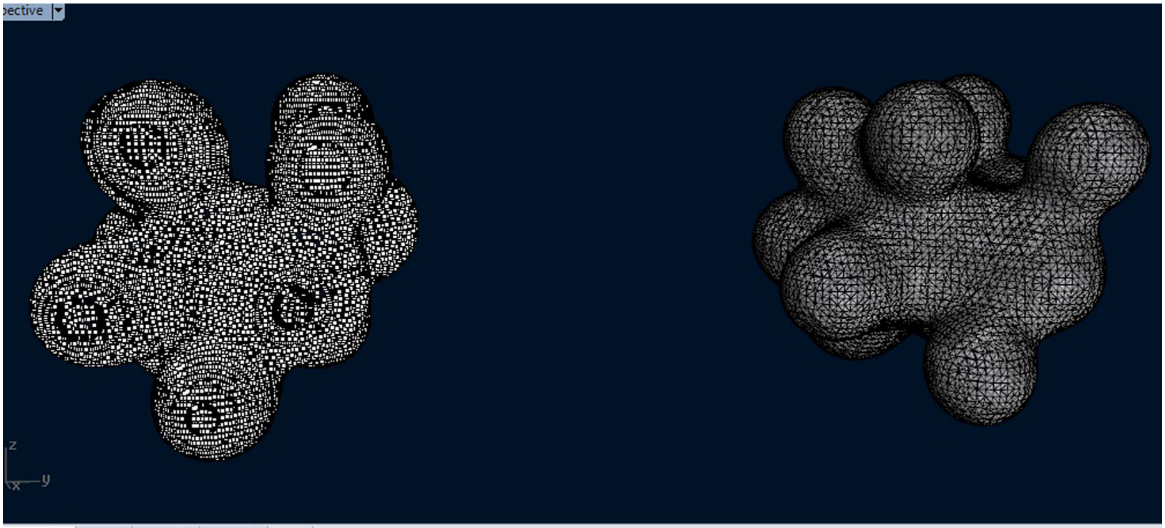
5.4 Morphing points



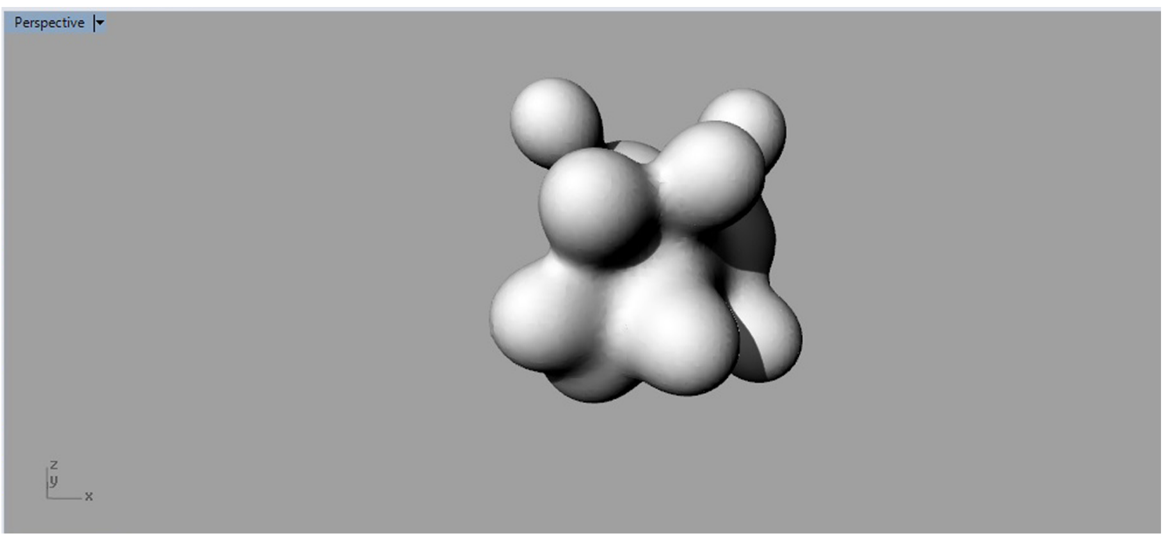
5.5 Growth Evolution



5.6 Meshing Surface

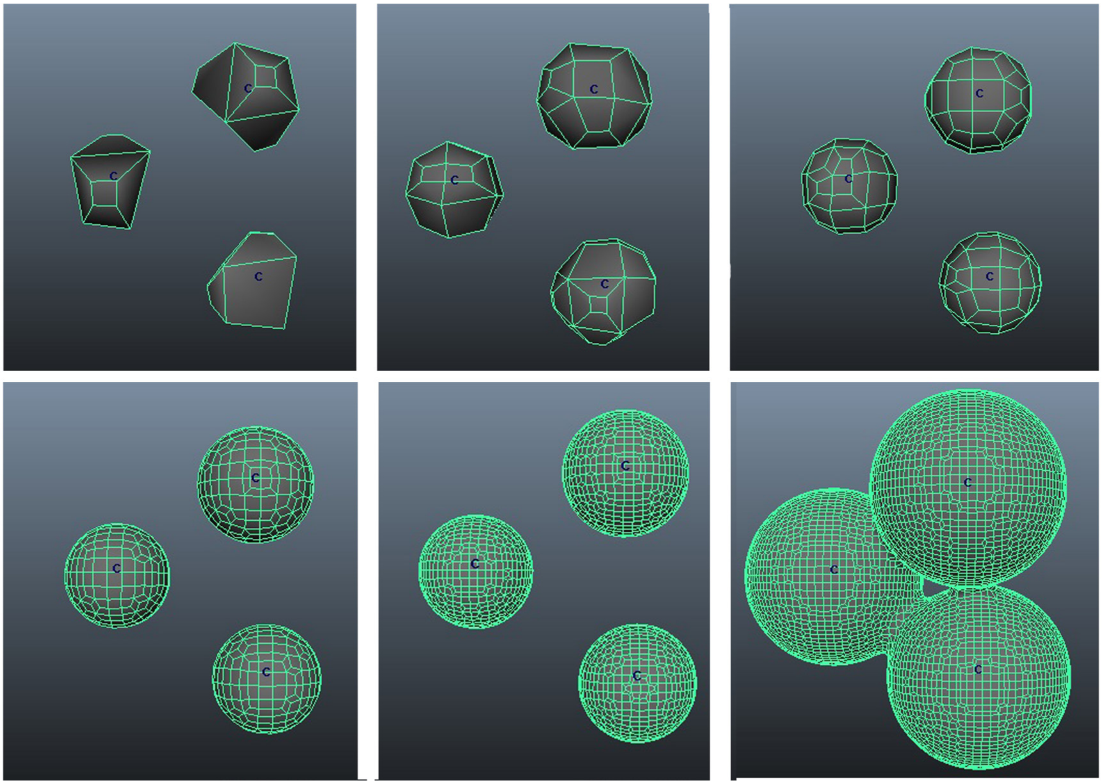


5.7 System of Points & Mesh

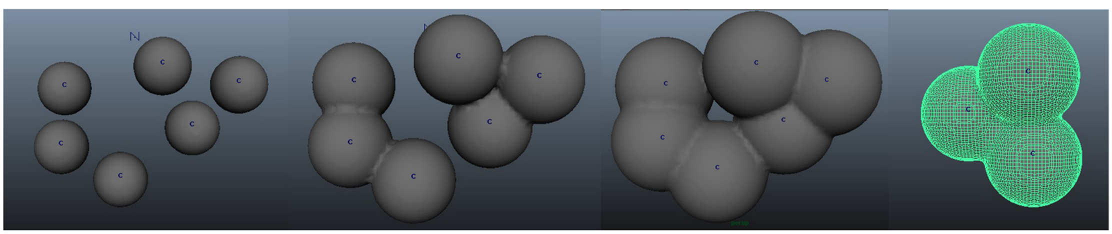


5.8 Surface derivated from metaballs

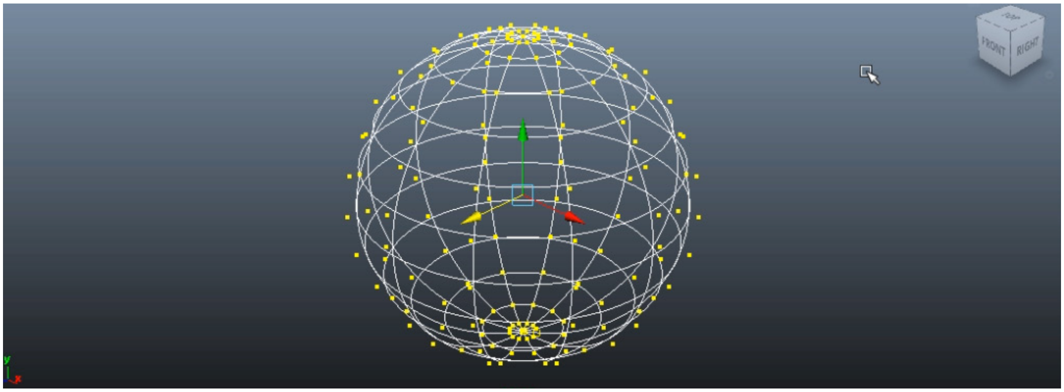
Metaballs Maya



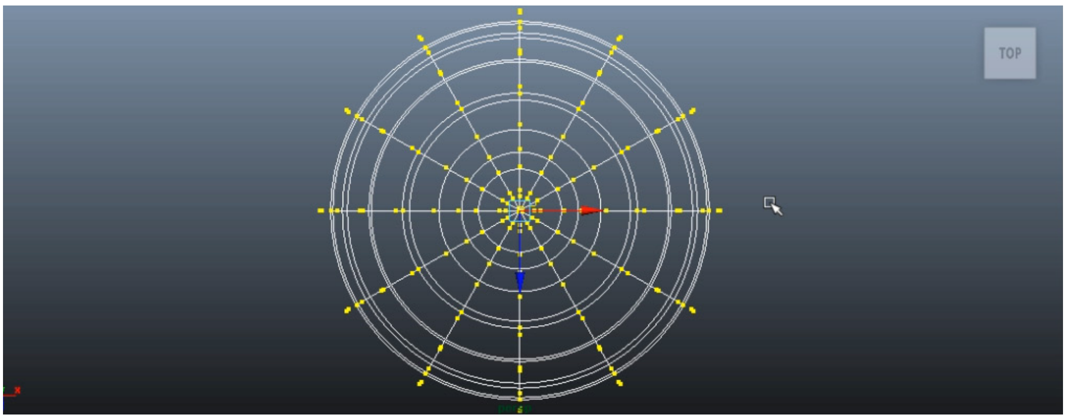
5.9 Redifining Growing Mesh



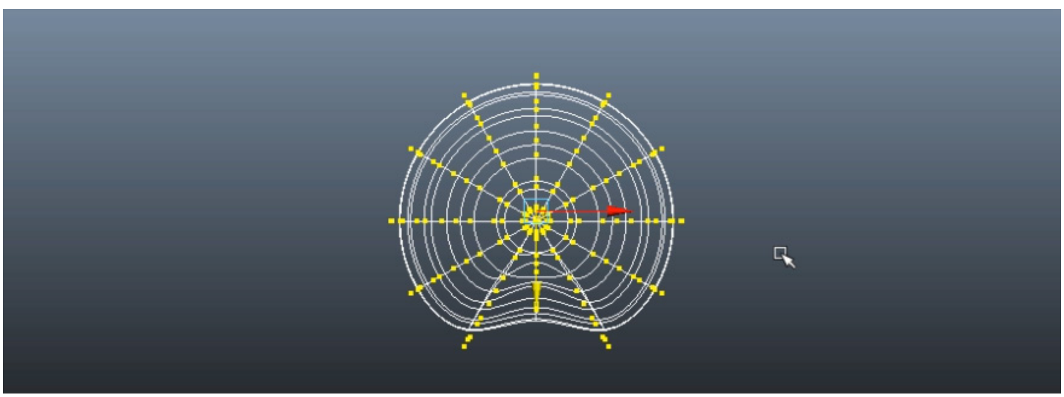
5.10 Morphing Evolution

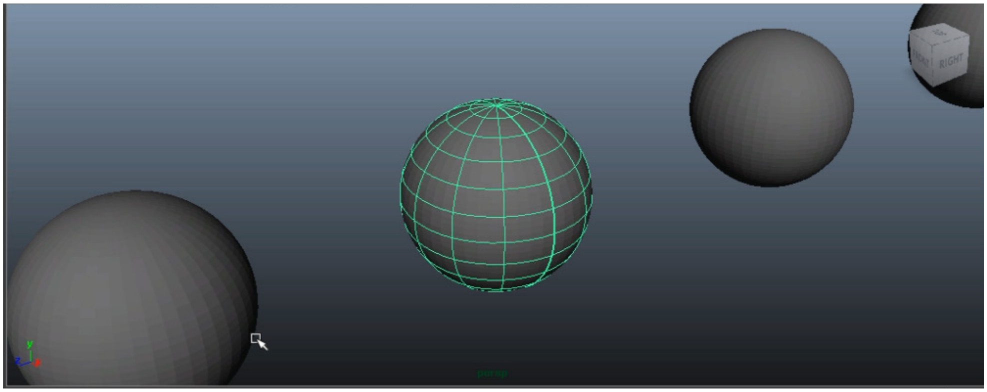


5.11 Tracing Greg Lynns Embriological House

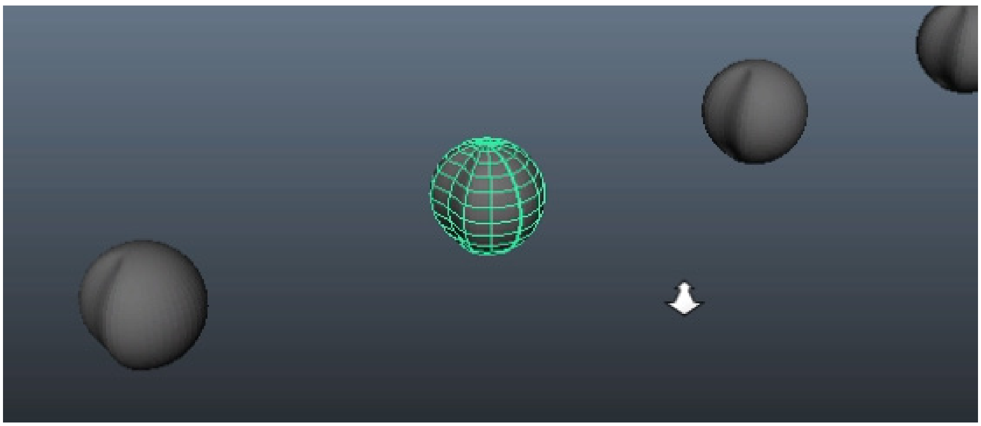


5.12 Control Points

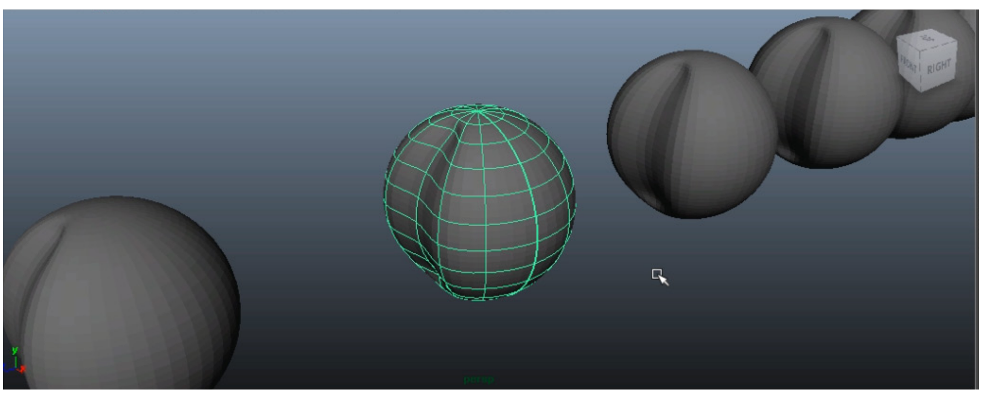

5.13 Manipulation Of Control points



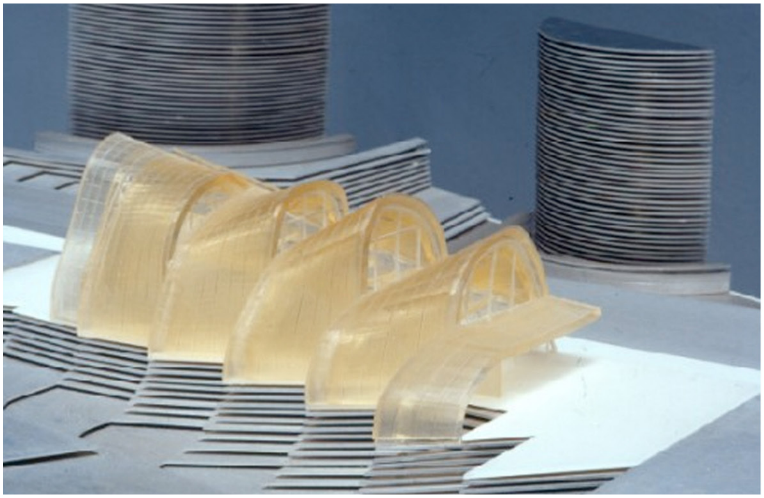
5.14 Linear Growth

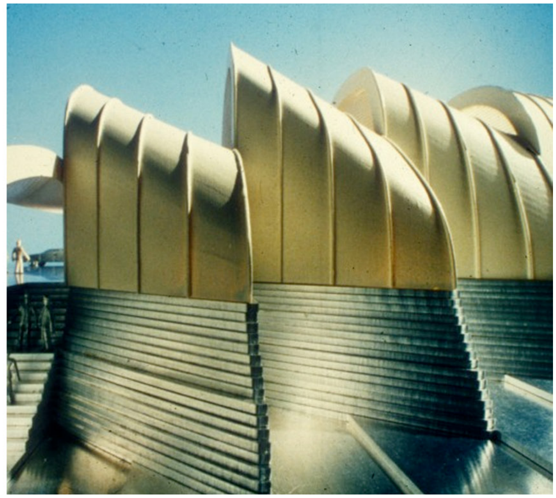


5.15 Families

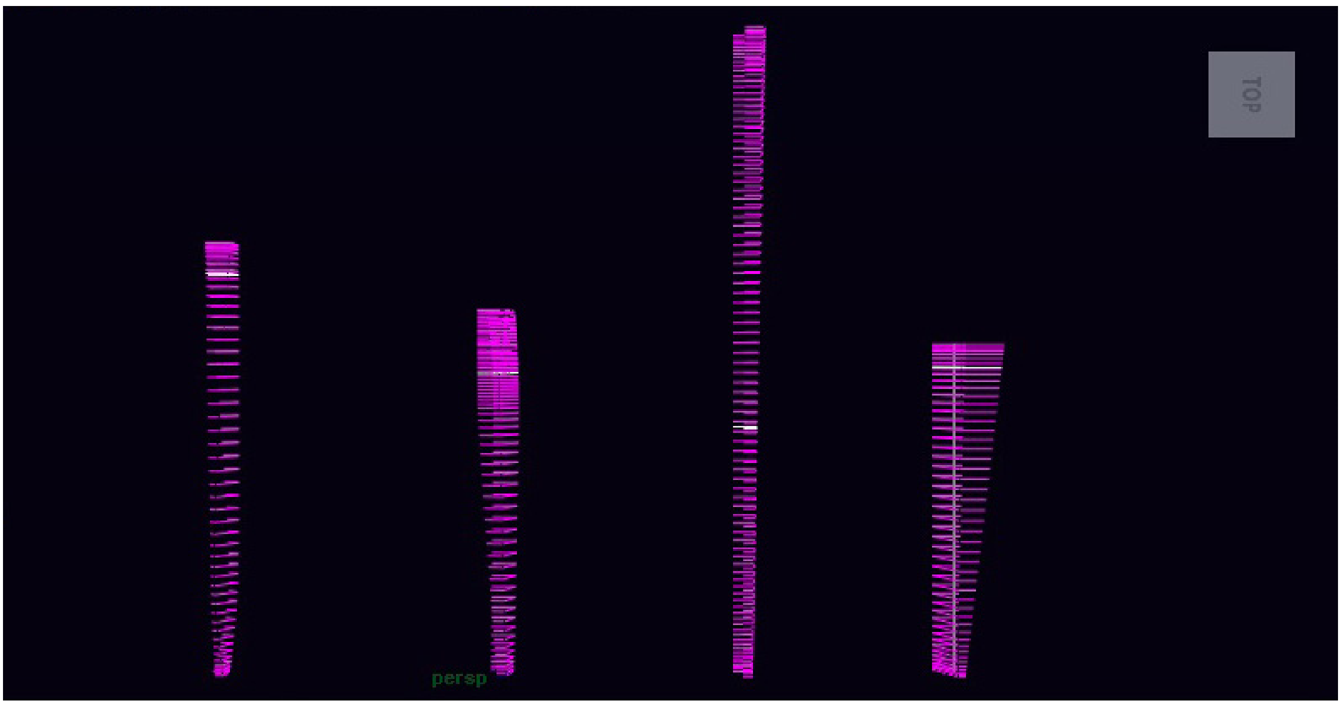


5.16 Linear transformation

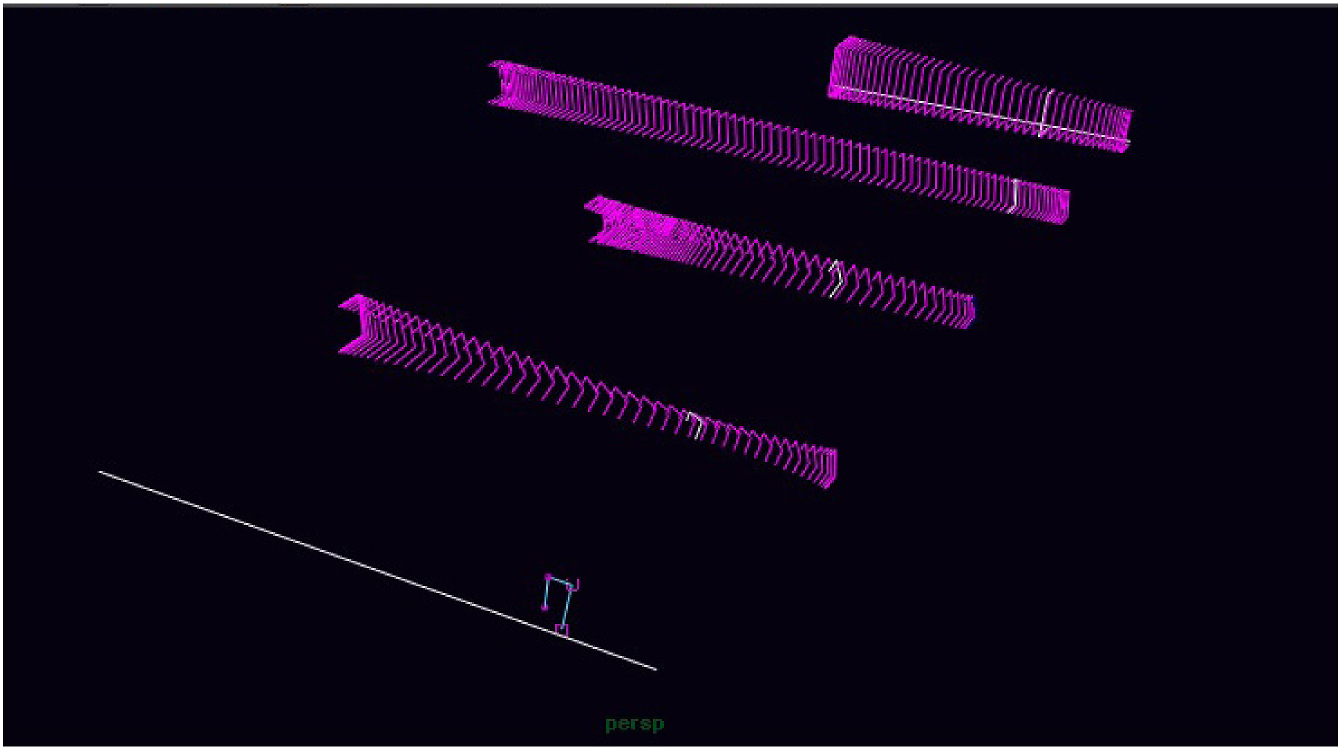




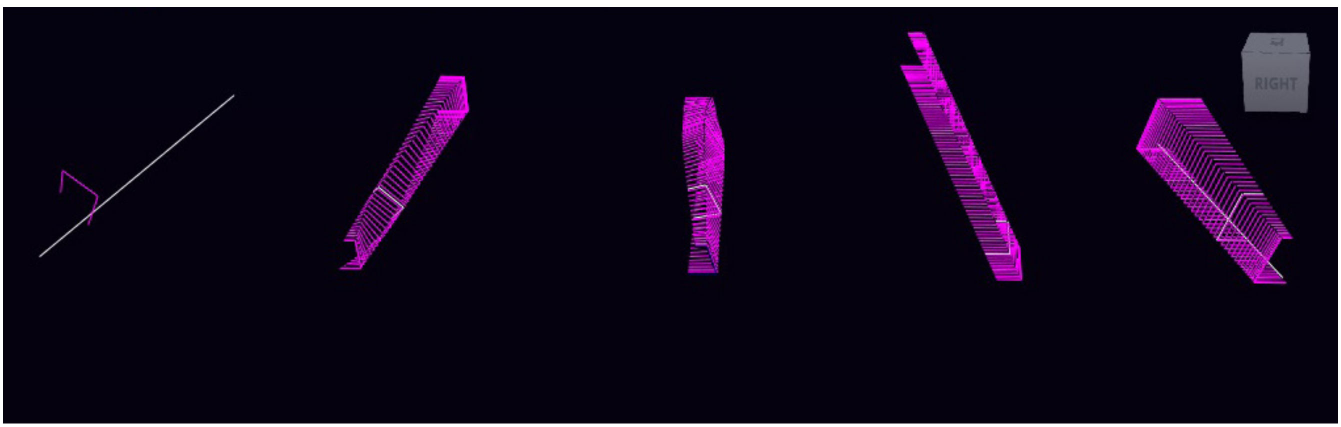
5.17 OMV H2 House - Greg Lynn - In : http://glform.com



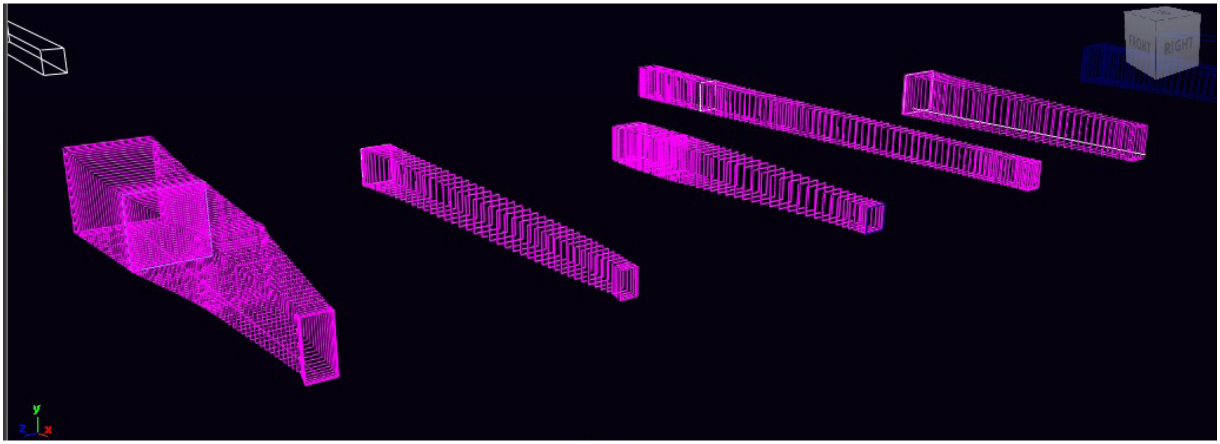
5.18Top View - Linear Morphosis

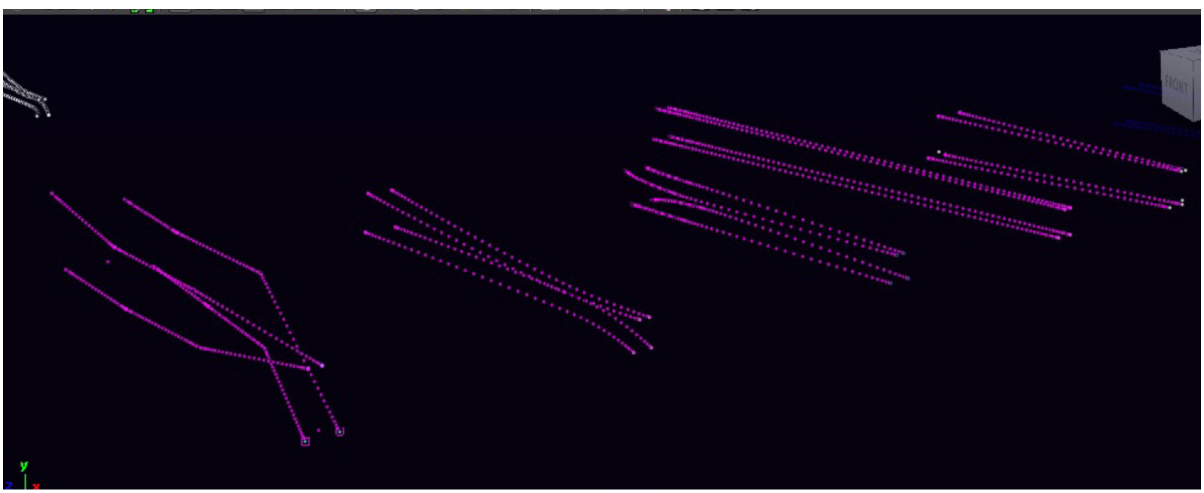


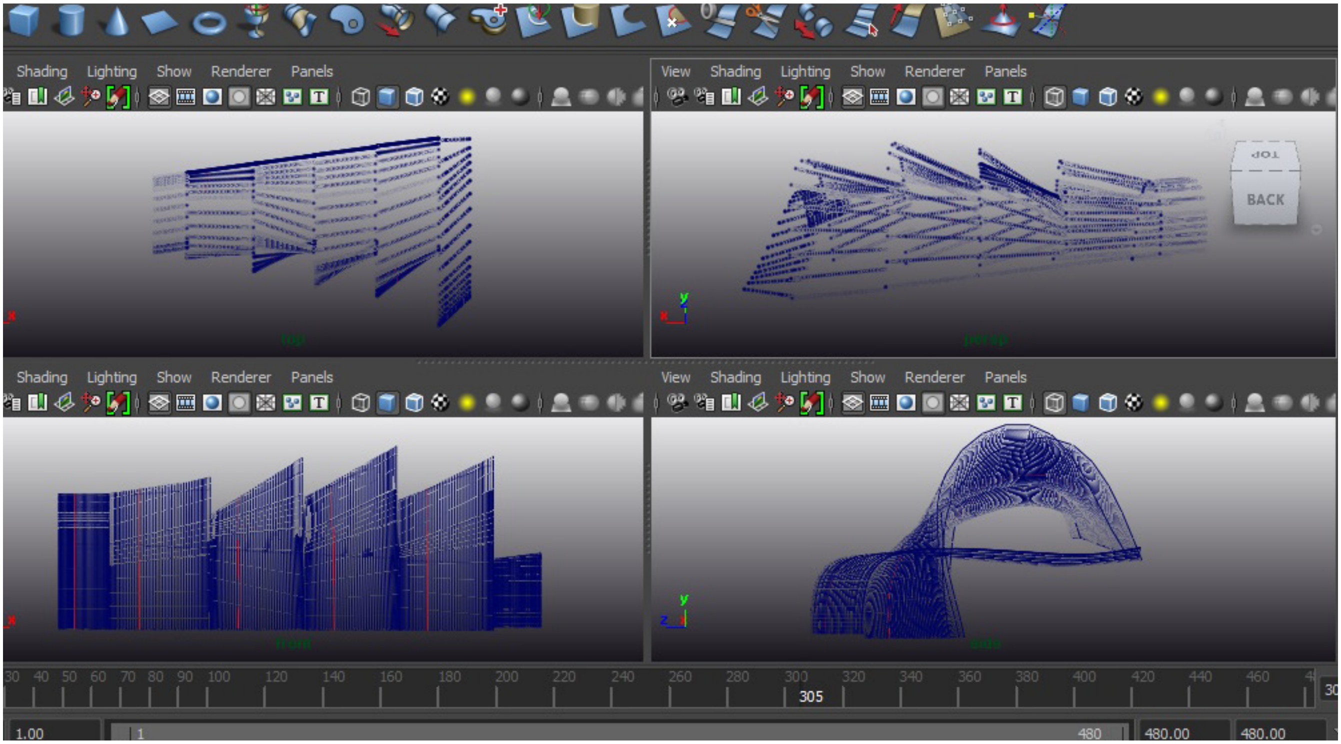
5.19 Node Linear Transformation



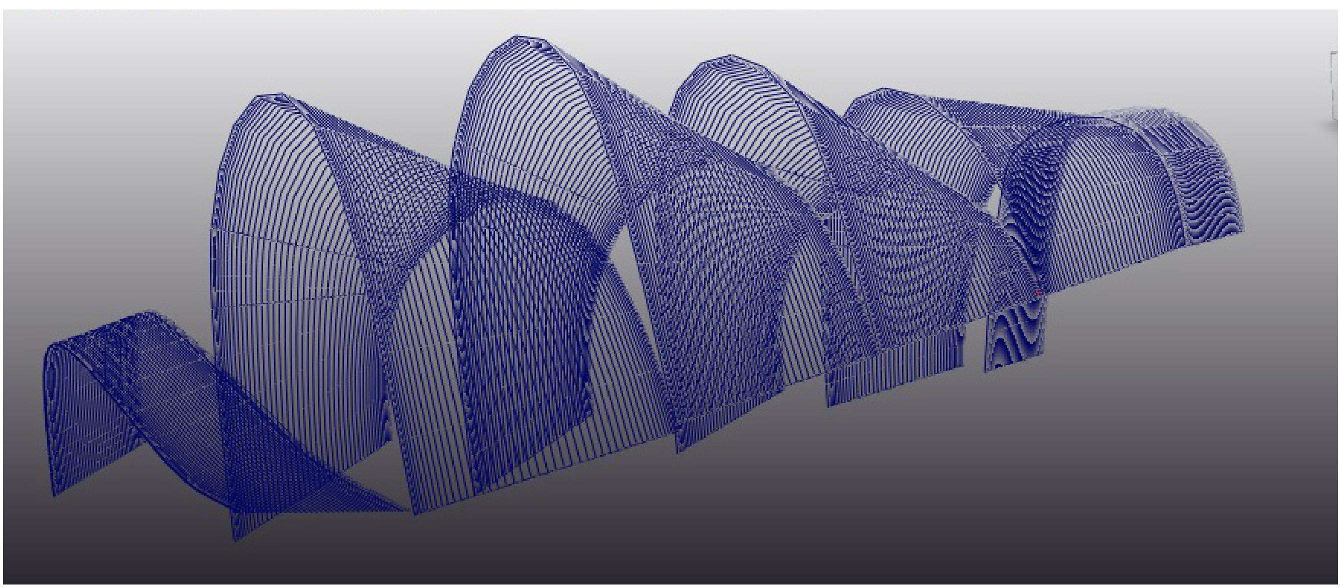
5.20 Equivalences Between Linear Transformations


5.21 Rectangular Gradual Linear Transformations

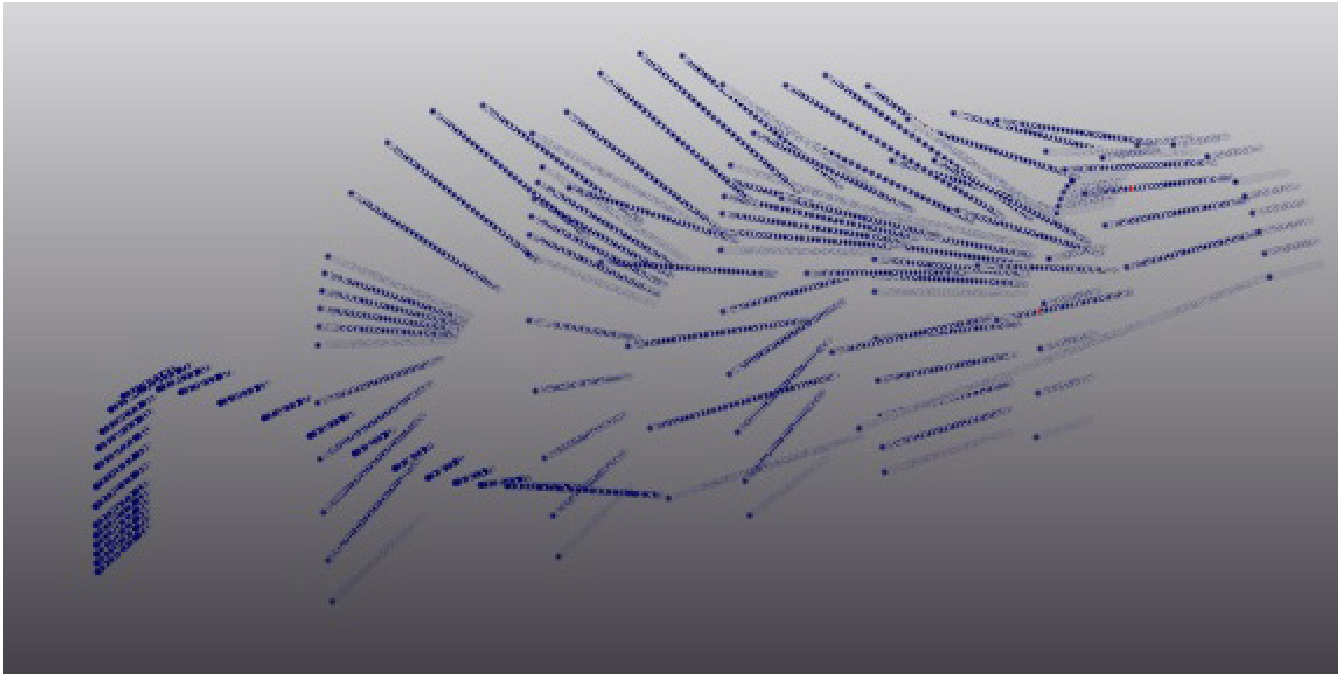

5.22 Point Transformation in Space



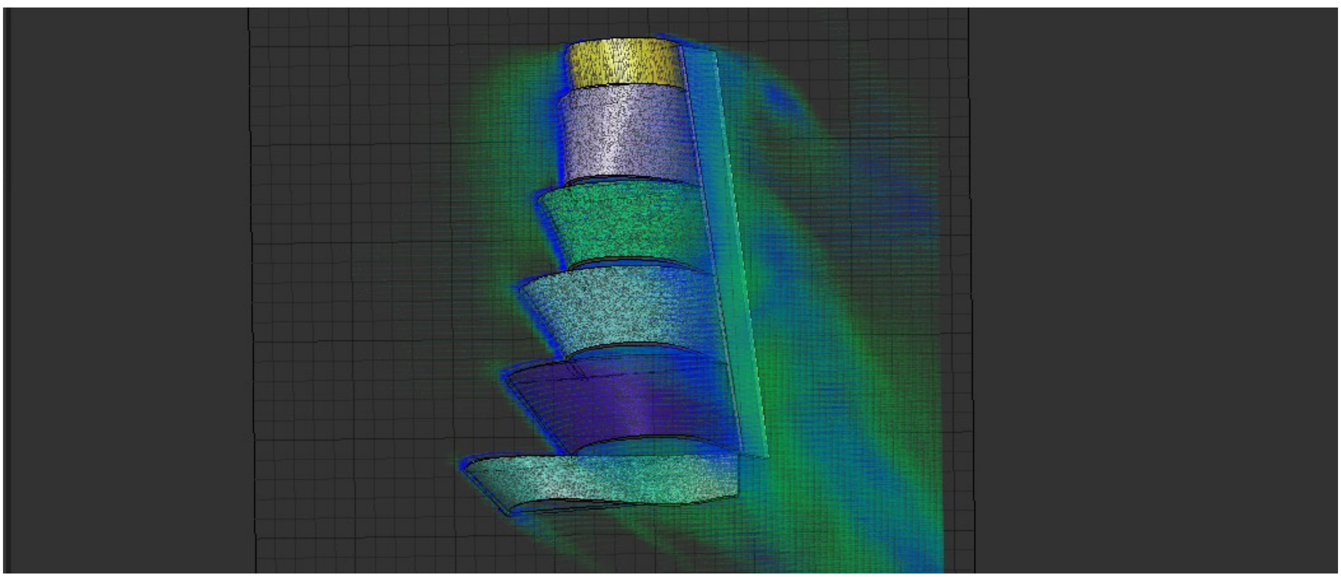
5.23 Form Finding Planimetry



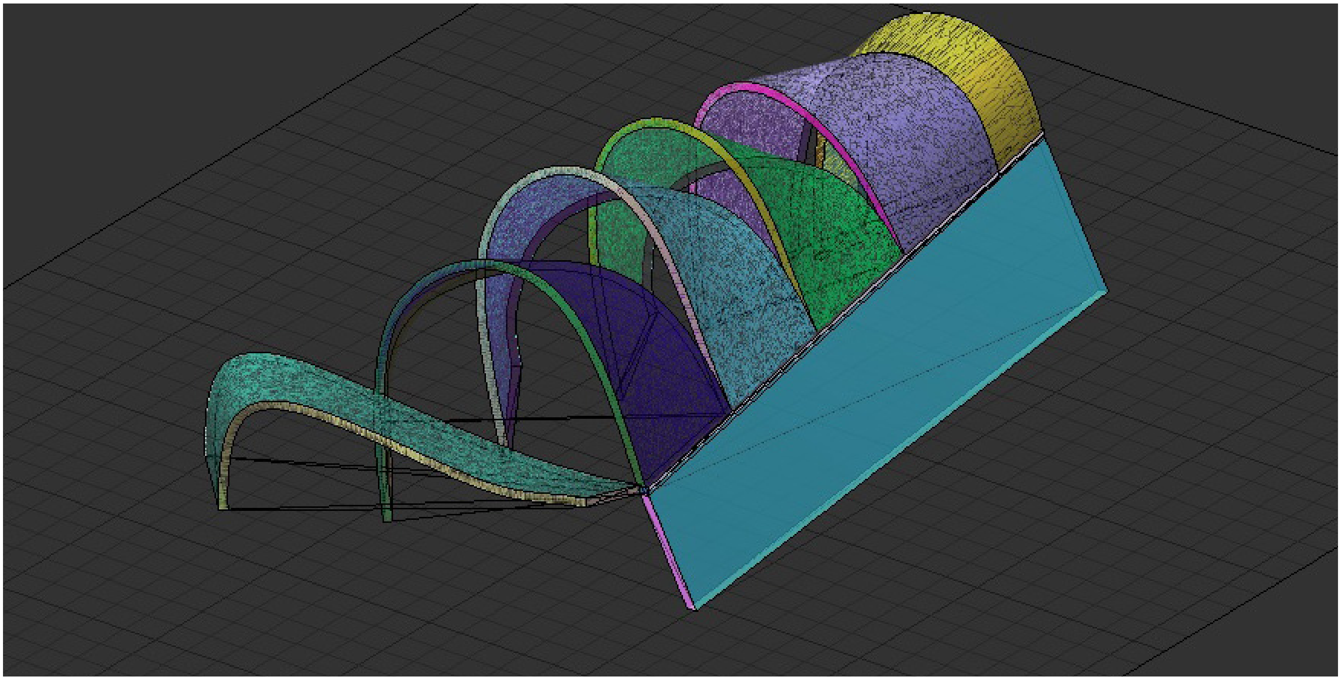
5.24 Surface morphological Progression



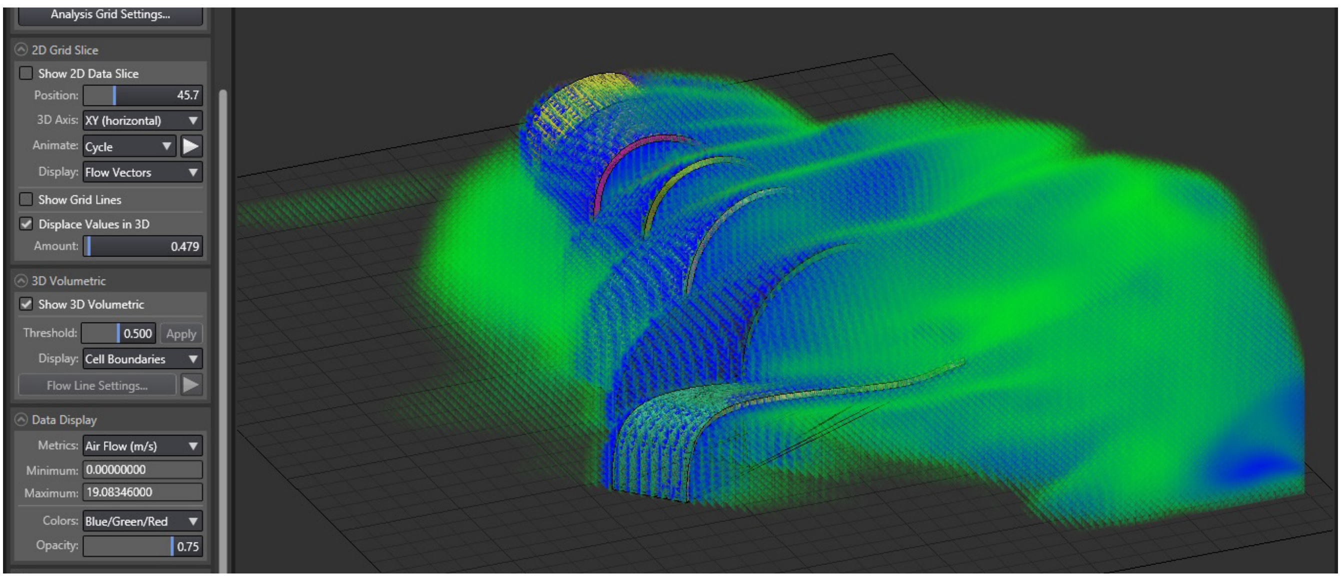
5.25 Point Morphological Progression



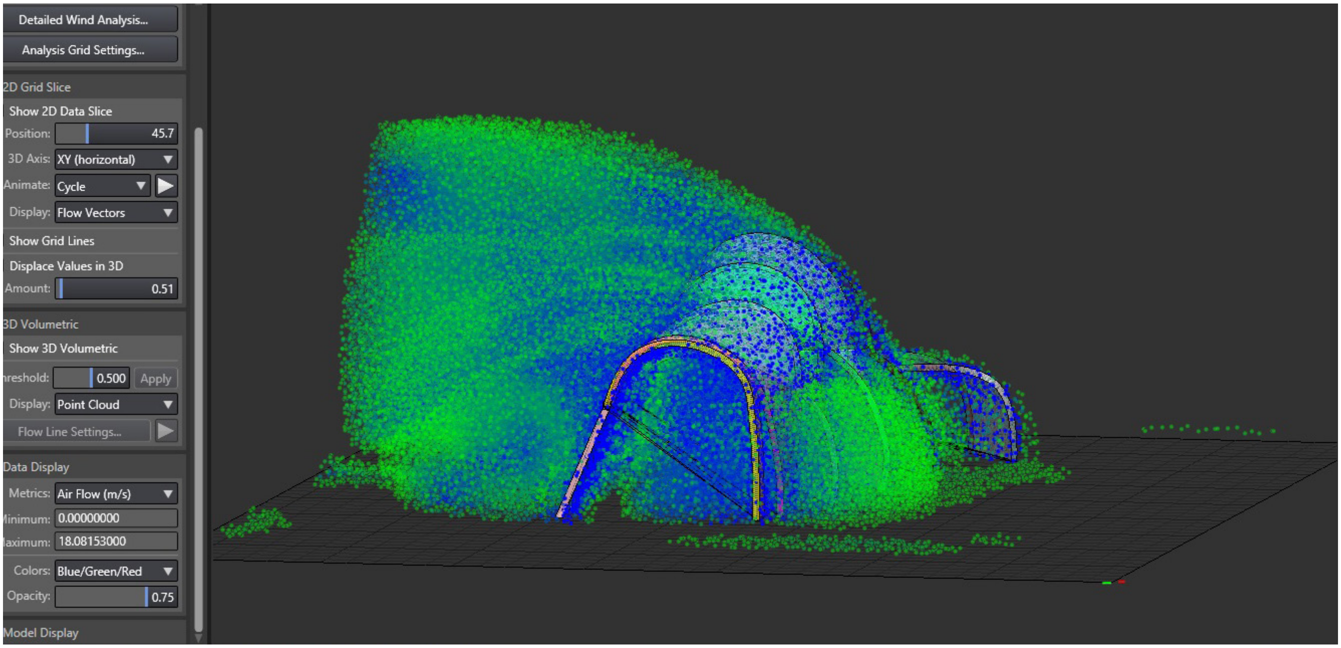
5.26 Top View Wind Behaviour



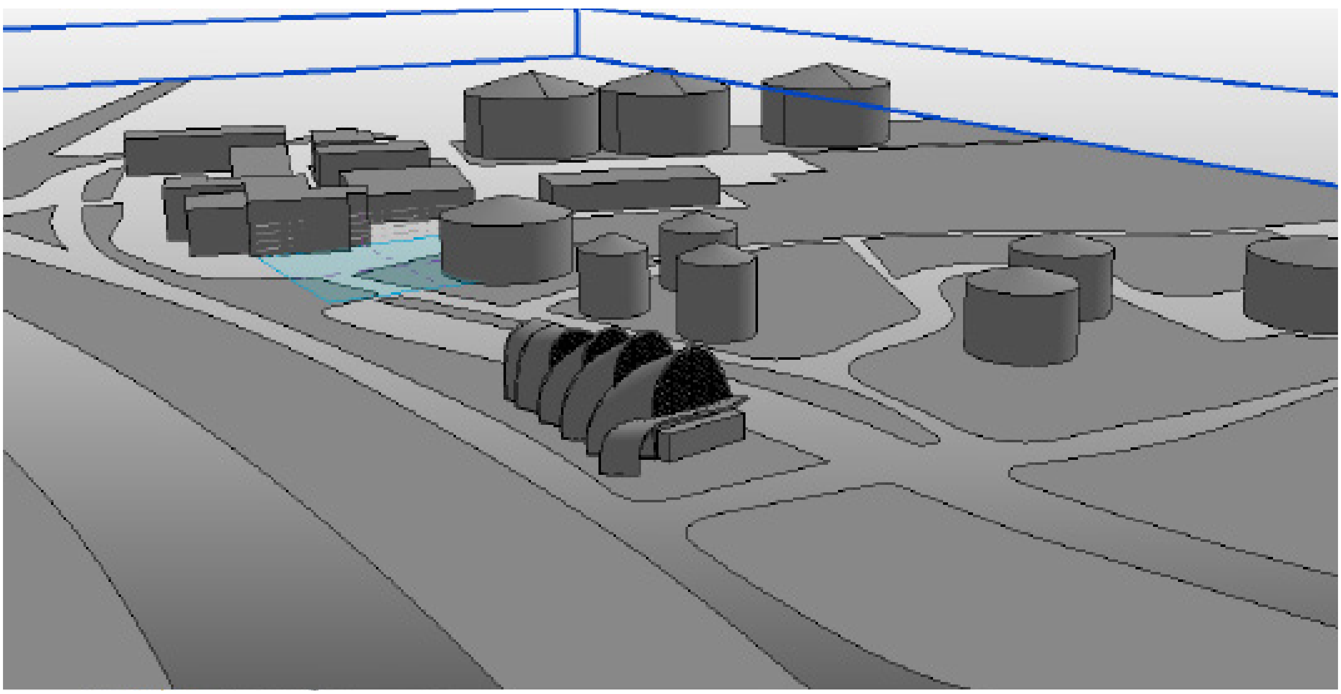
5.27 OMV H2 House - Before Wind Analysis-



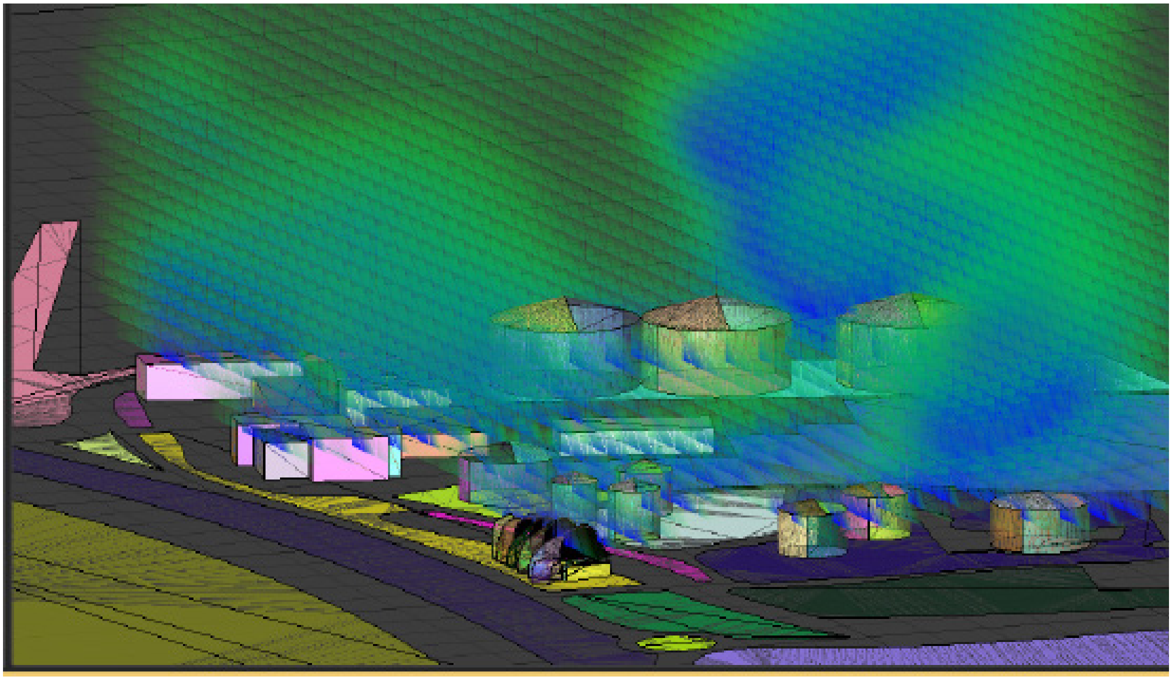
5.28 Wind Layer Behaviour

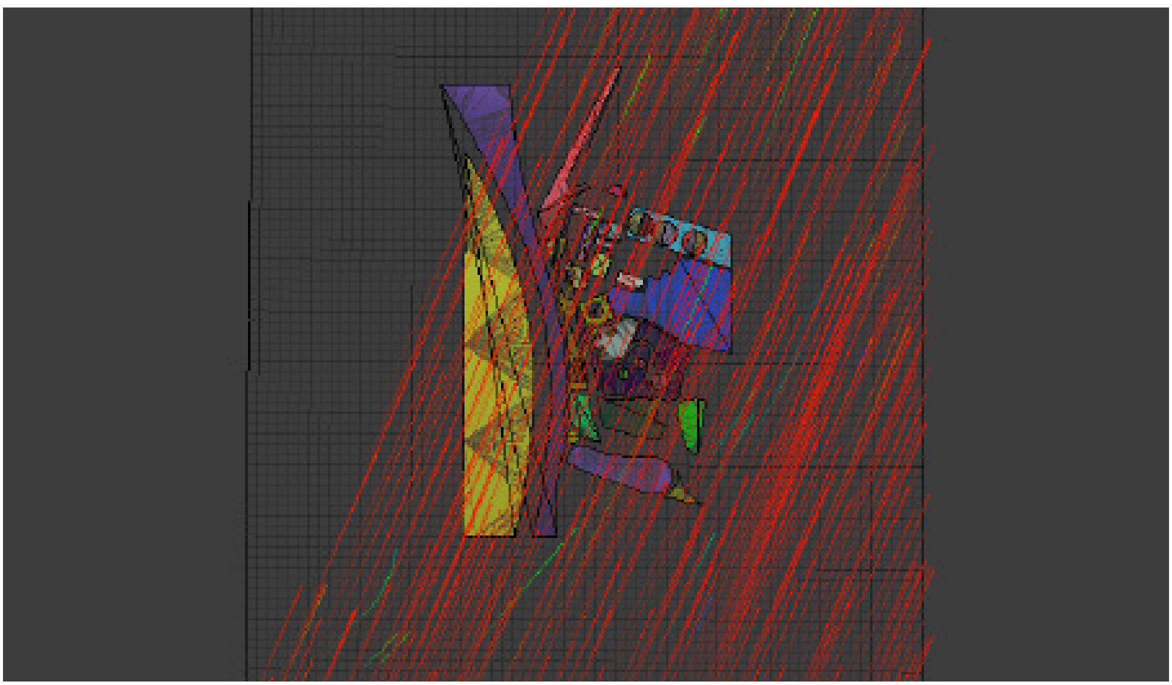


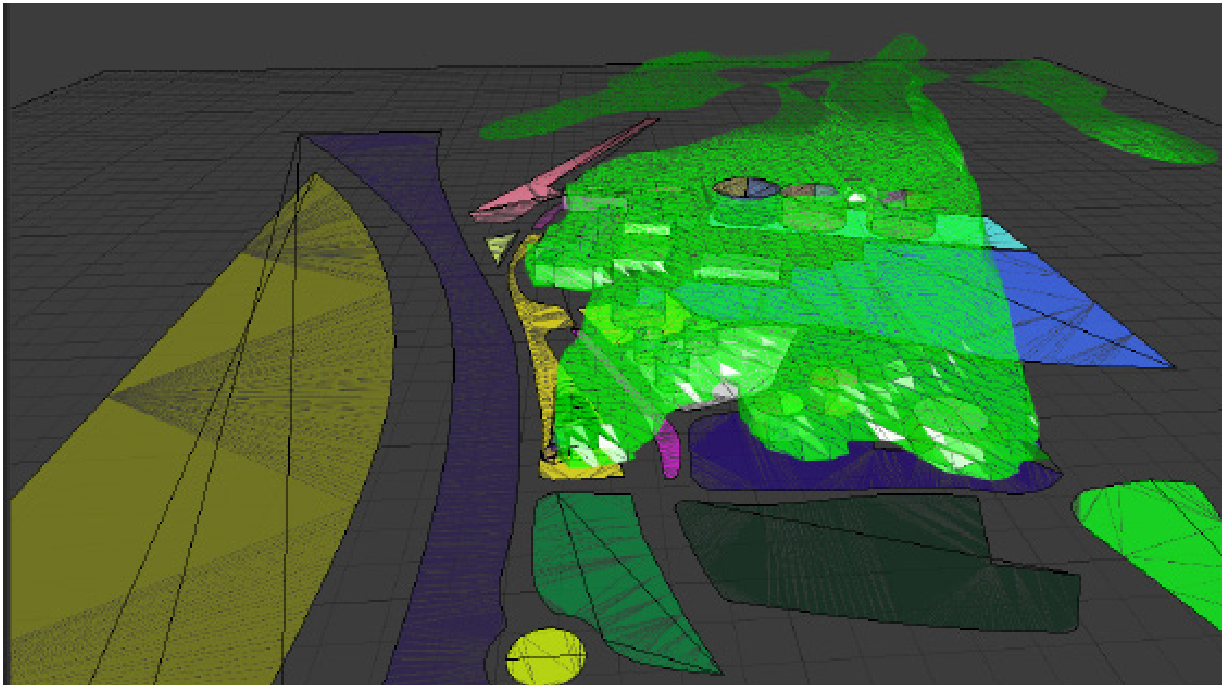
5.29 Back View - Point Particle Behaviour-

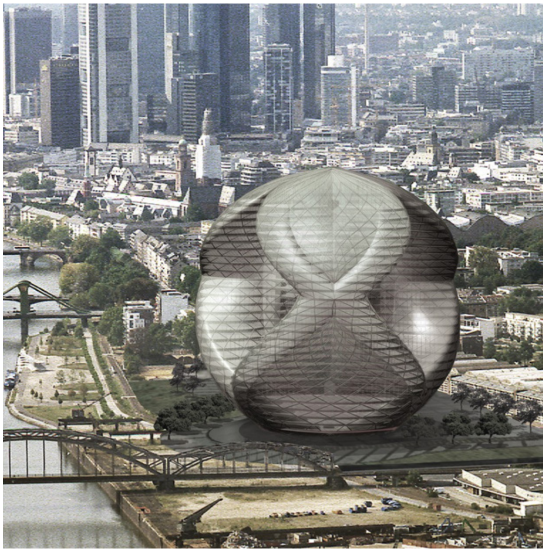


5.30 Model in context


5.31 Wind Contextual Analysis

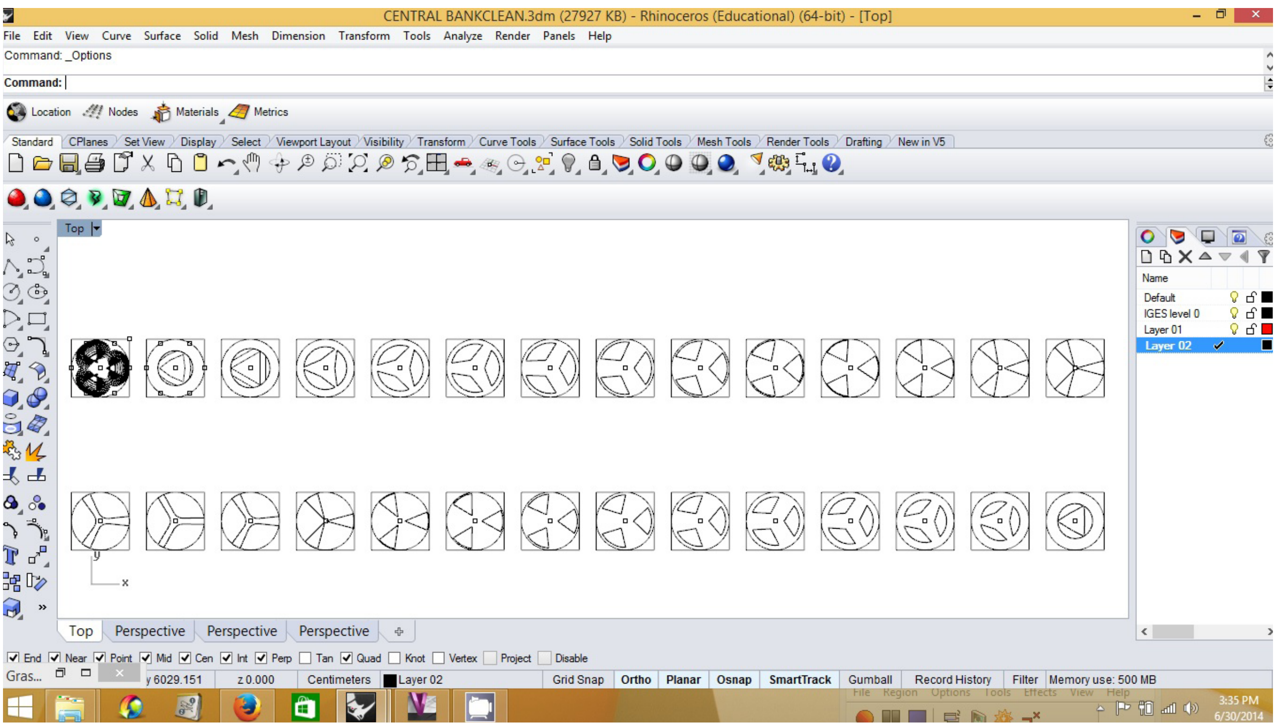

5.32 Top View Wind Contextual Analysis


5.33 Mesh Surface Coming from Wind Behaviour

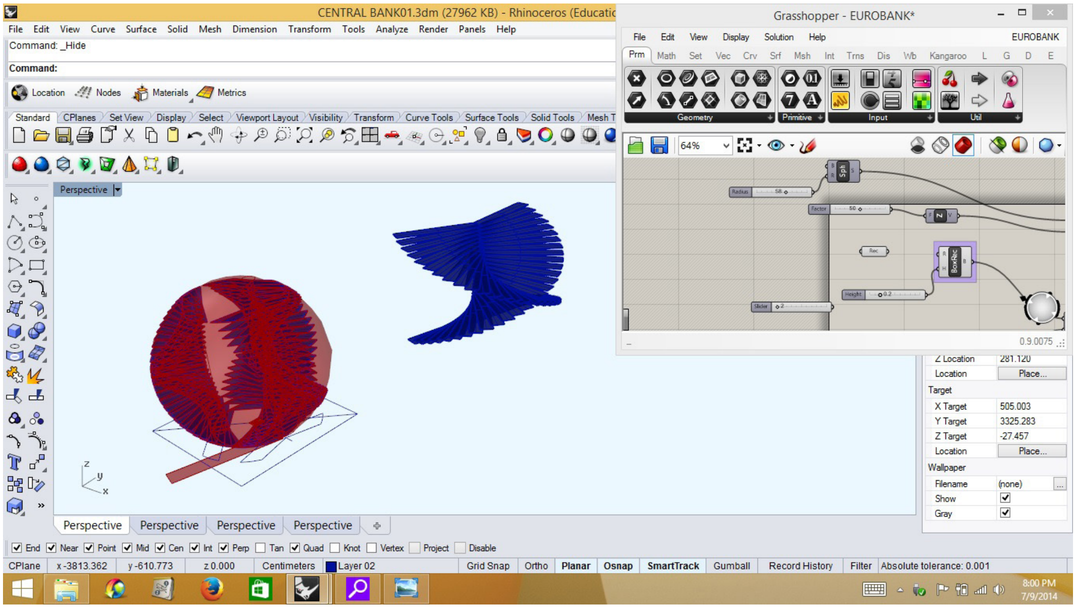


5.34 European Central Bank
In : http://glform.com

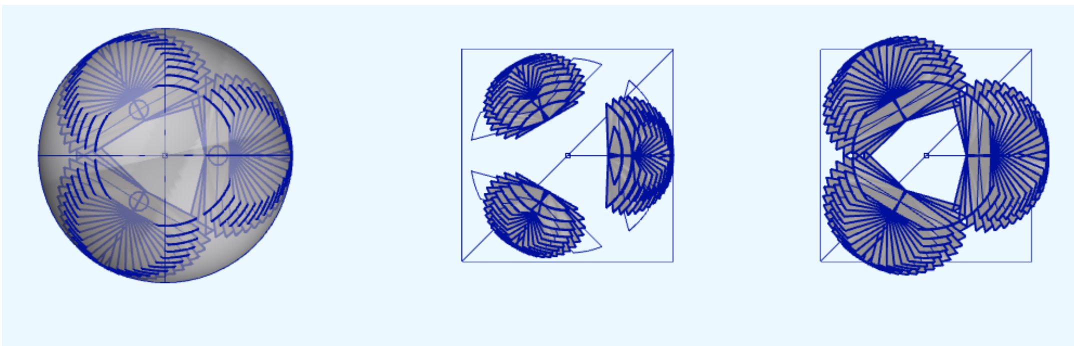
5.35 European Central Bank Front Perspective
In : http://glform.com



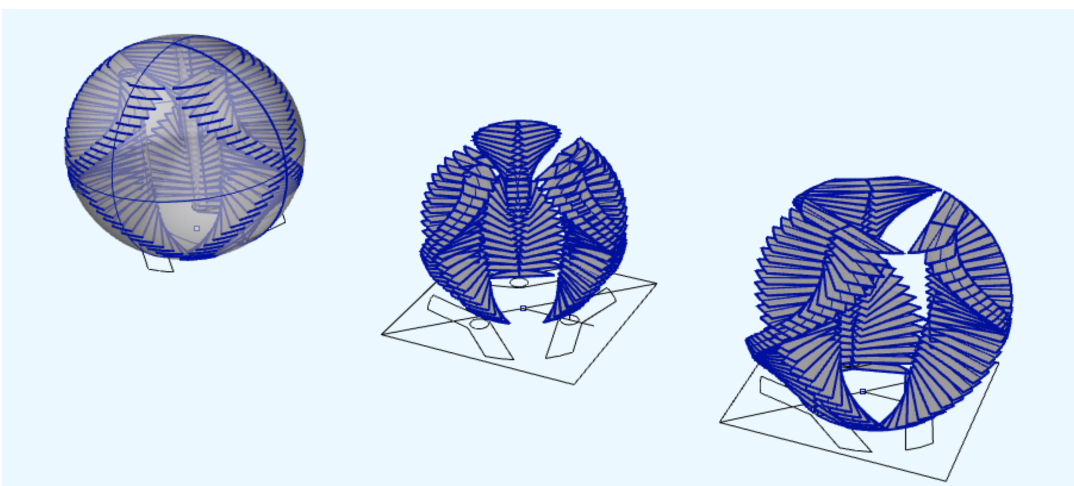
5.36 European Central Bank Floors Generated On Rhinoceros



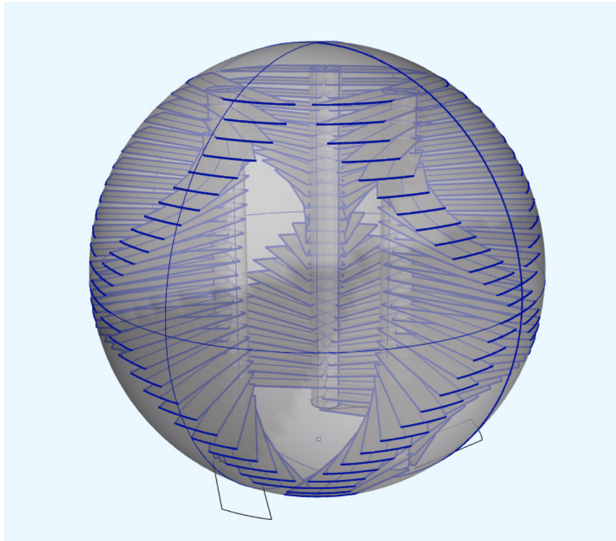
5.37 Algorithmic Definition of European Central Bank (grashopper)



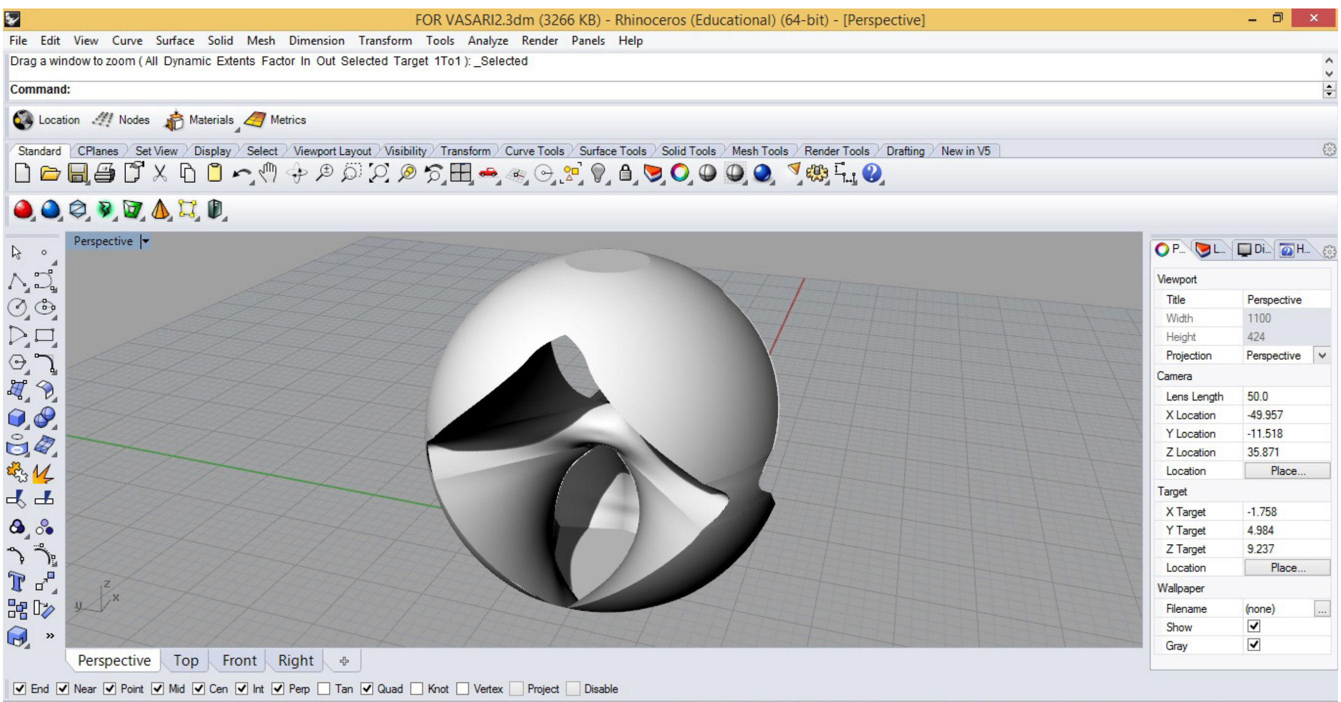
5.38 Top View -



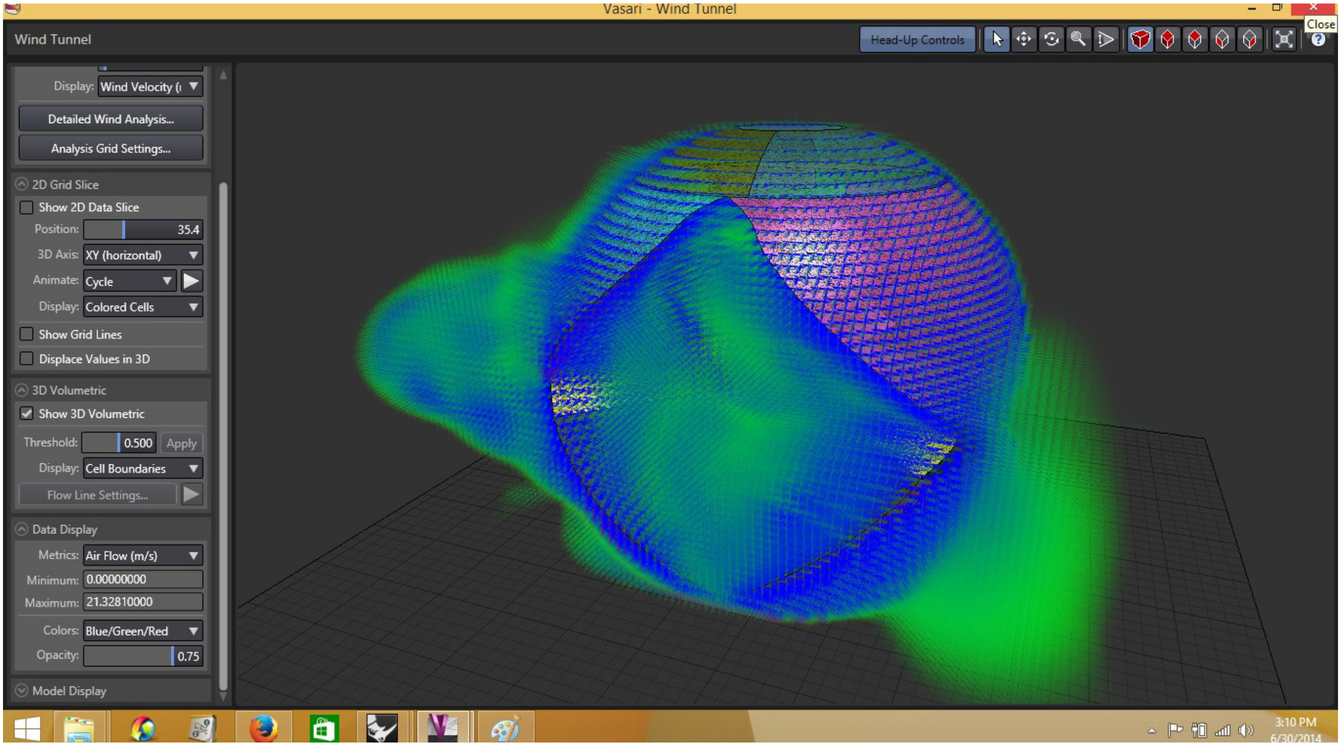
5.39 Discrete Elements Of The General Grammar Shape



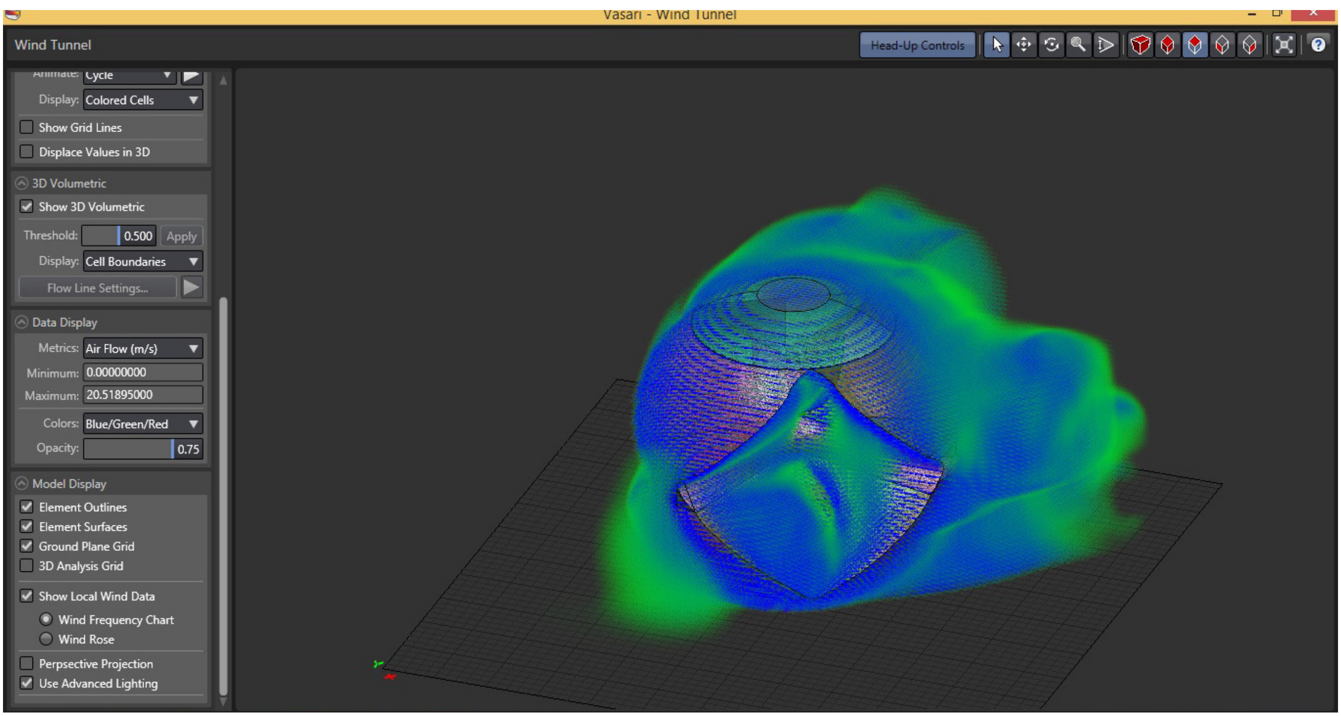
5.40 Grammar shape Elements



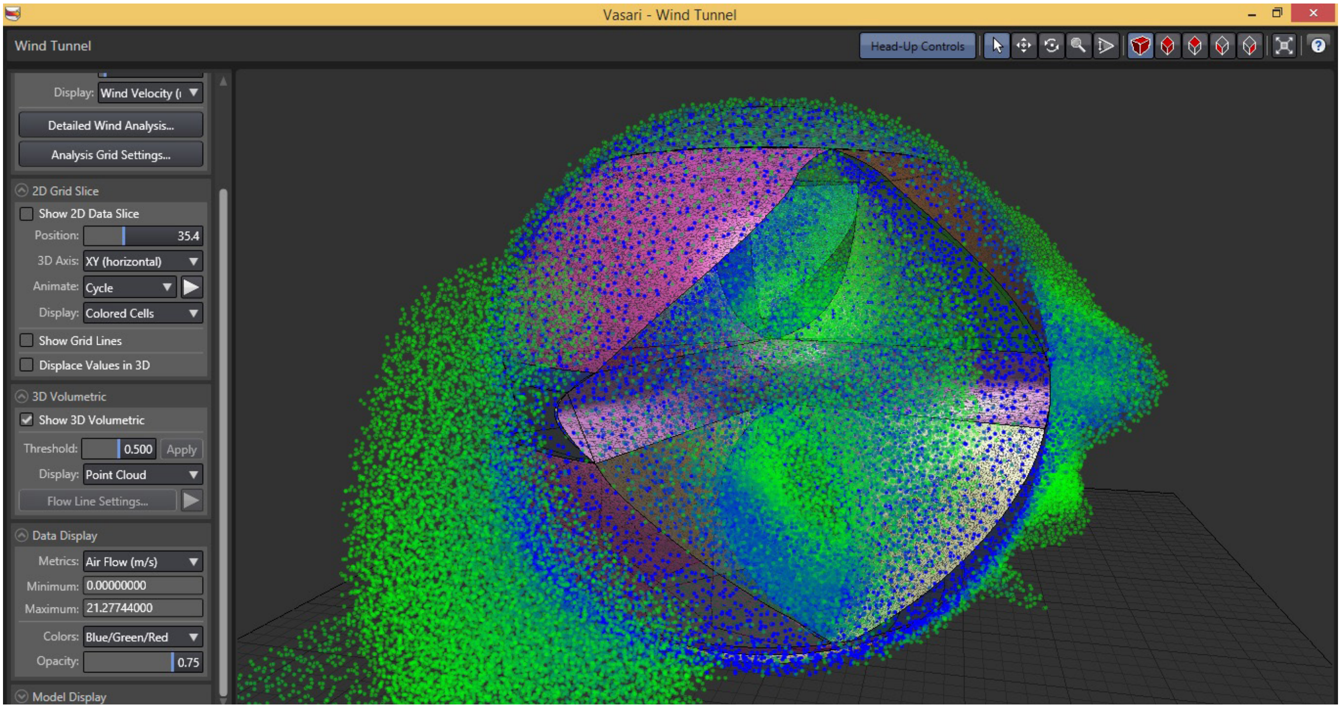
5.41 Solid Definition Of the project



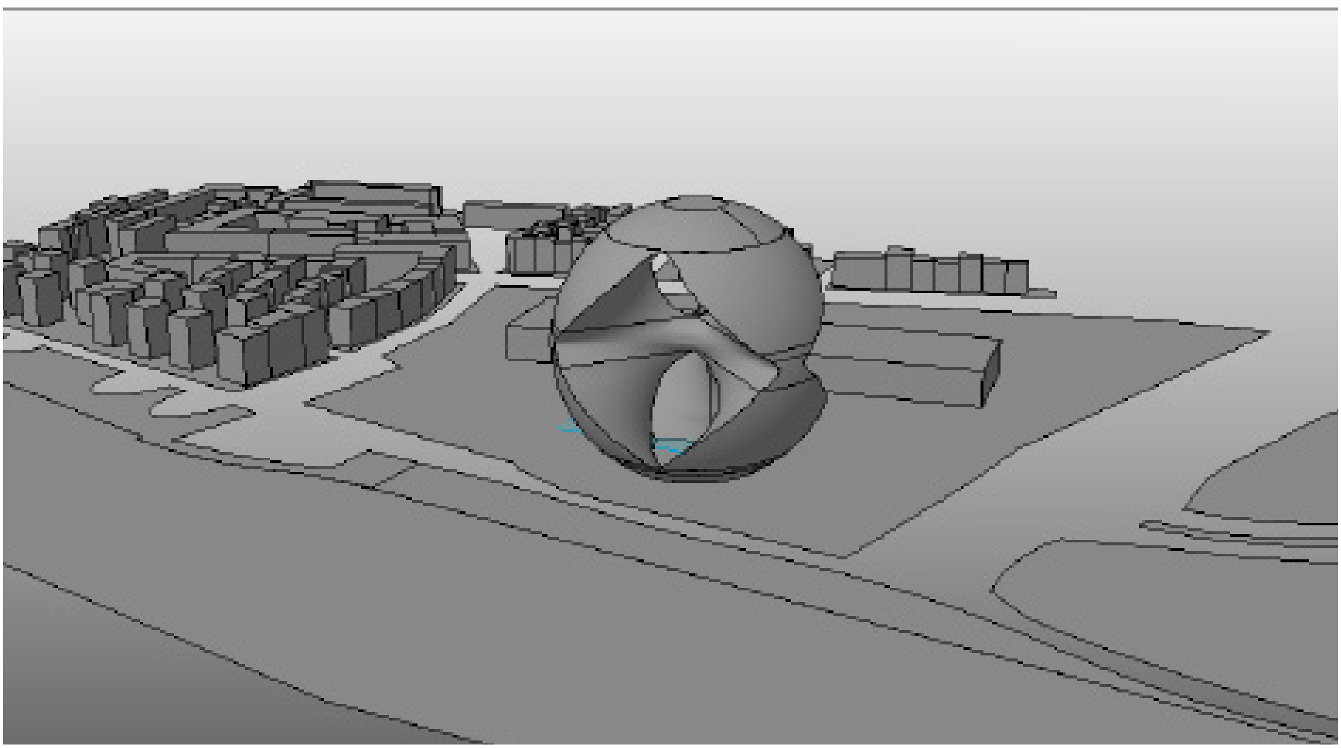
5.42 Layer Wind Analysis - Void Analysis-



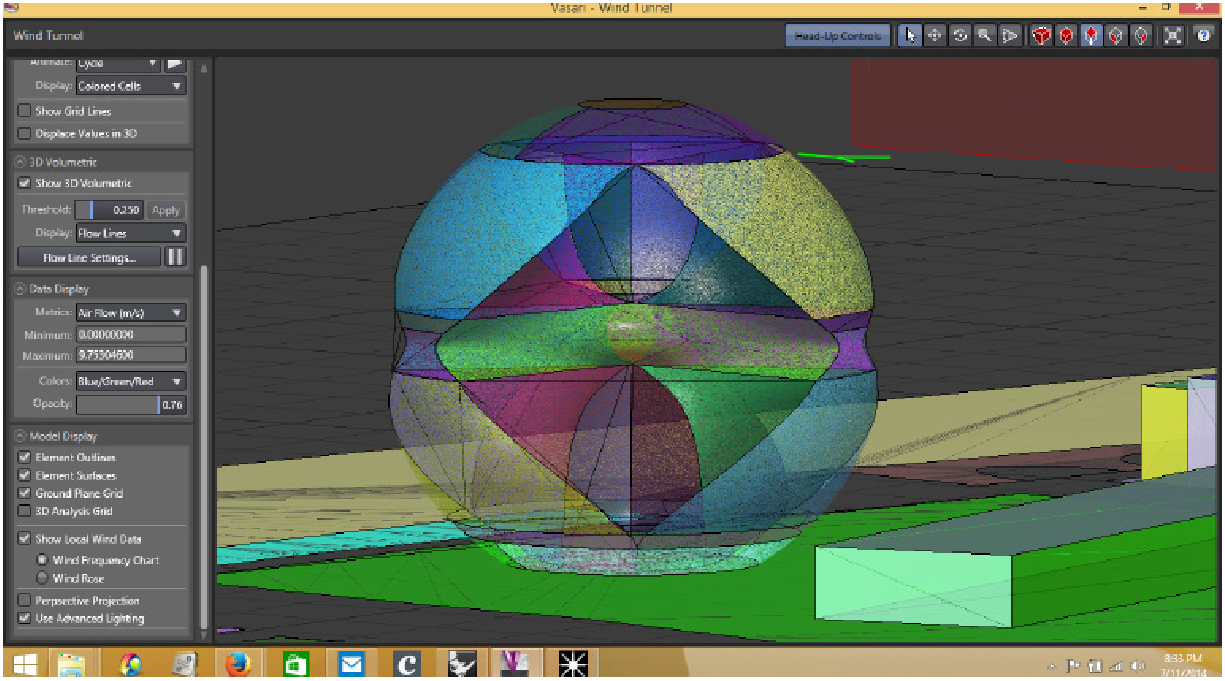
5.43 Layer Wind Analysis - General Shape Analysis-



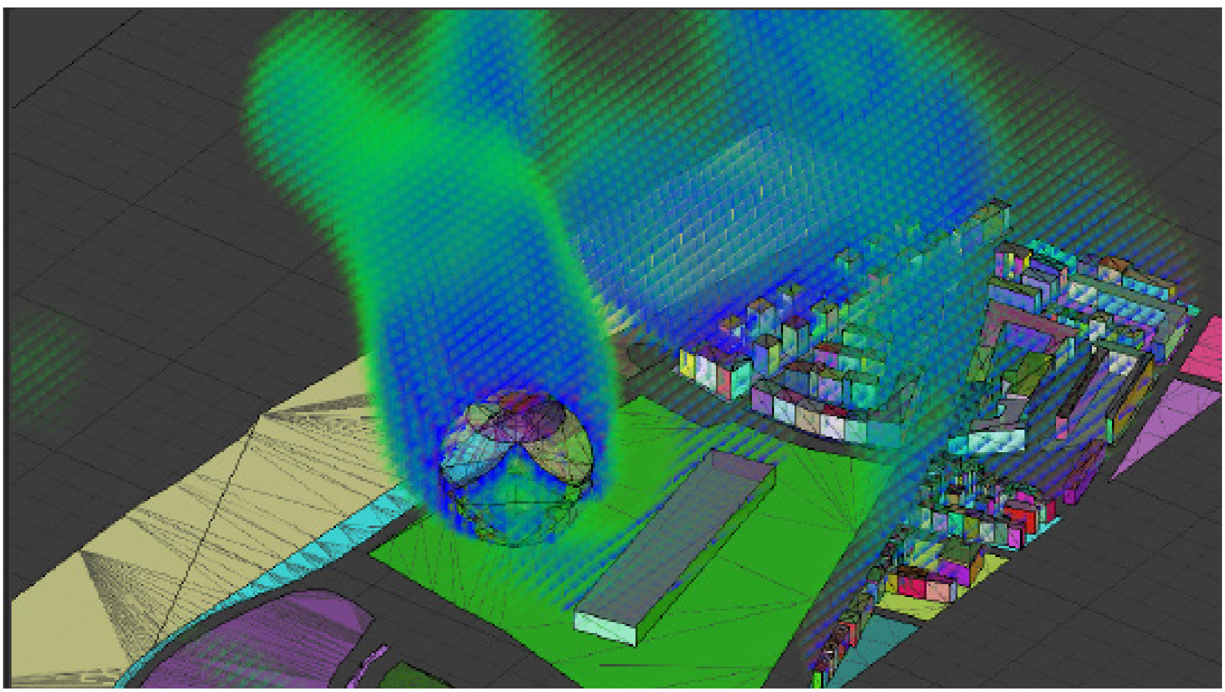
5.44 Particle Wind Analysis



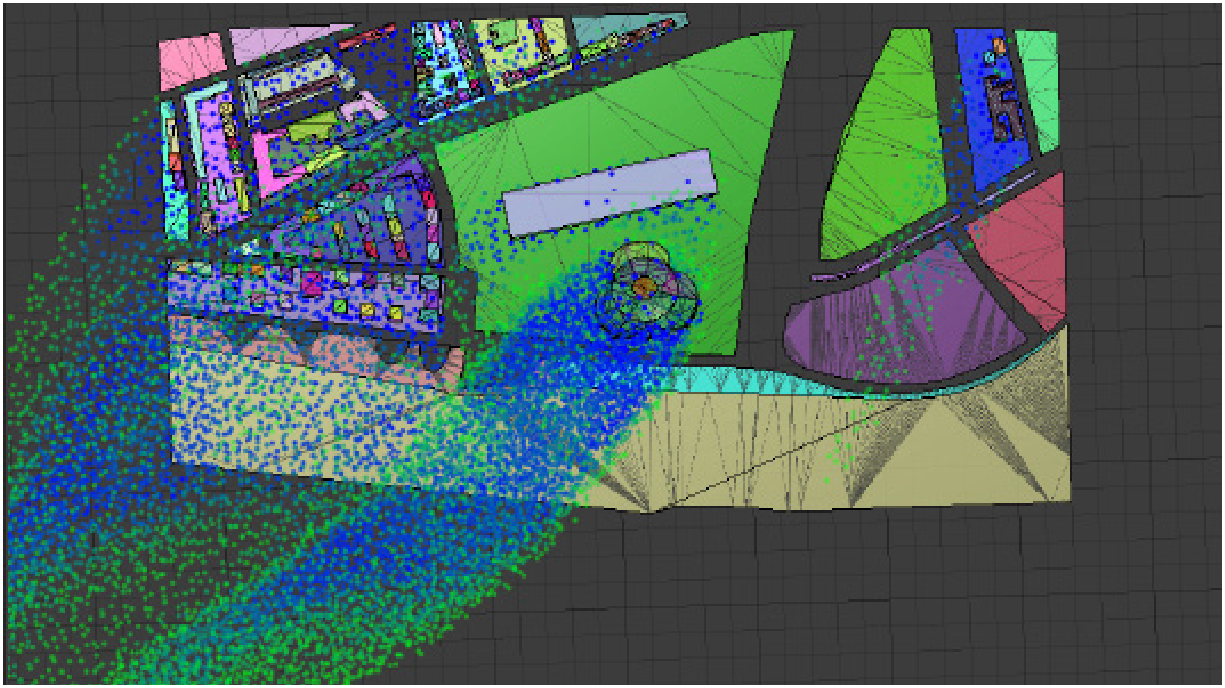
5.45 Model In Context

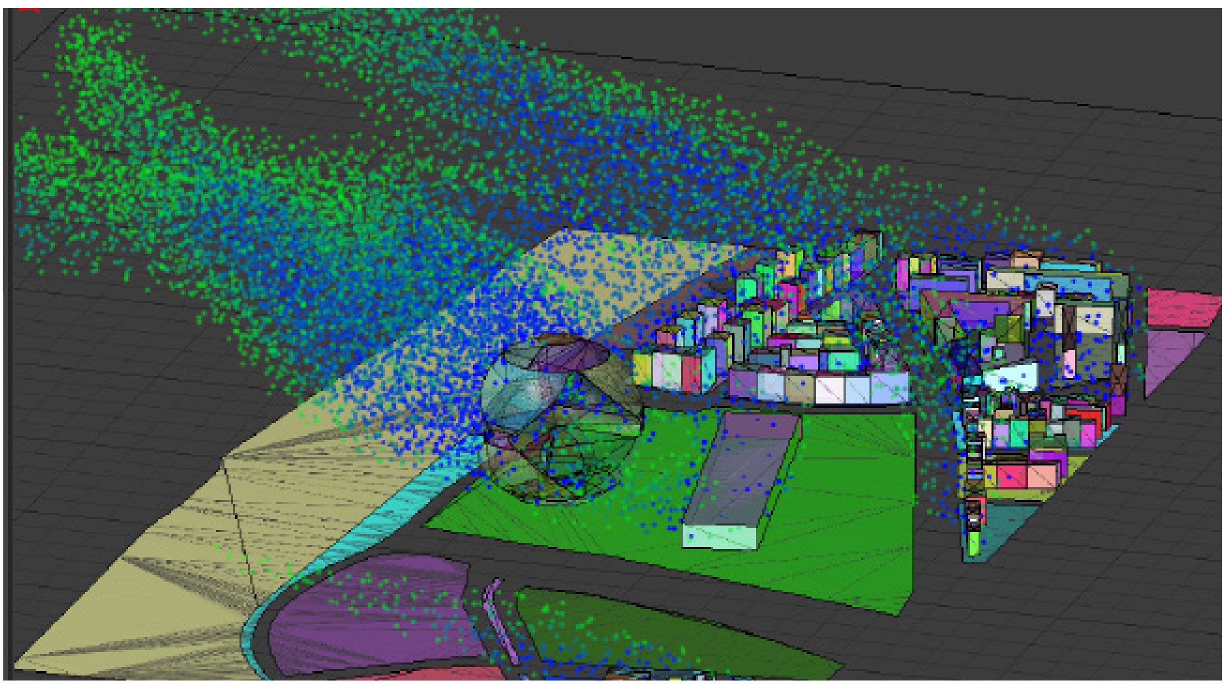


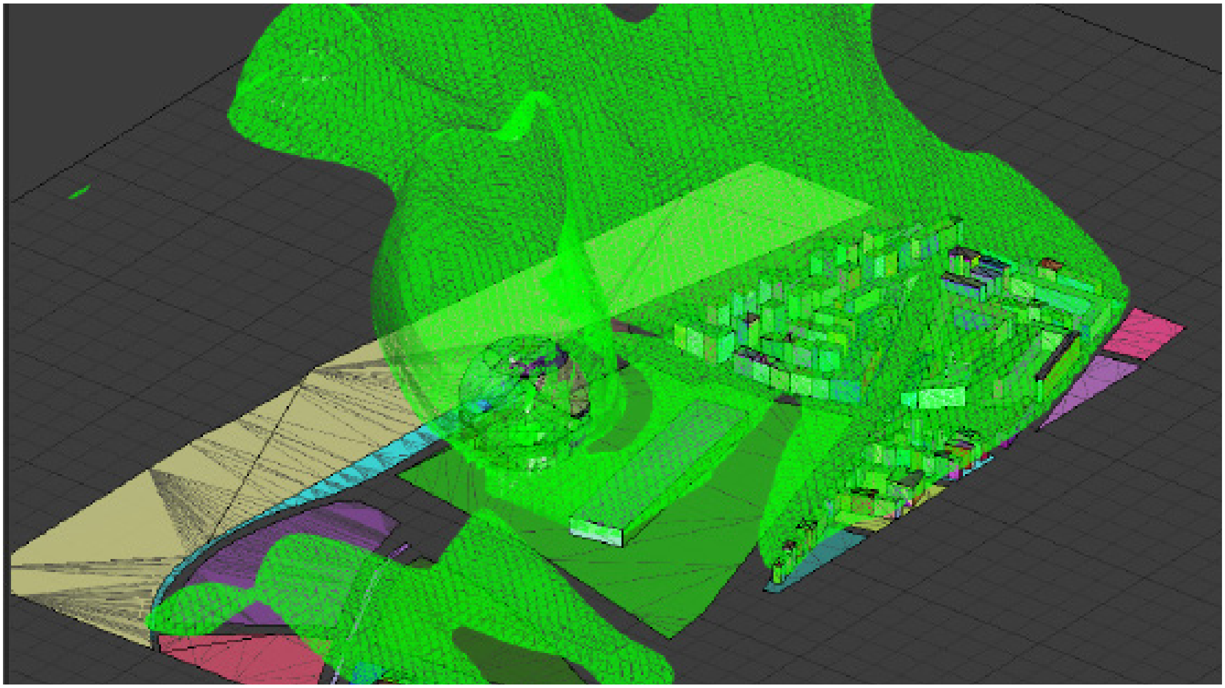
5.46 Surface Before Analysis



5.47 Wind Behaviour On Site


5.48 Top View Wind Behaviour On Site


5.49 Particles Wind   On Site



5.50 Wind Mesh Surface

Images

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