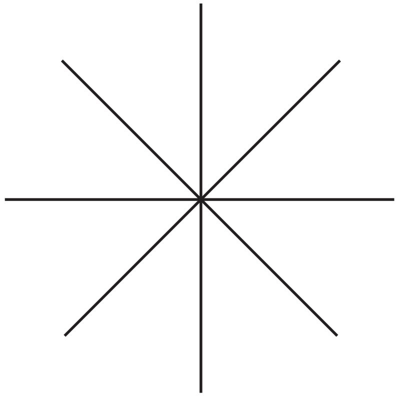

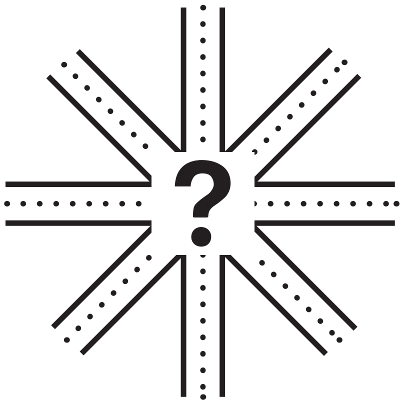

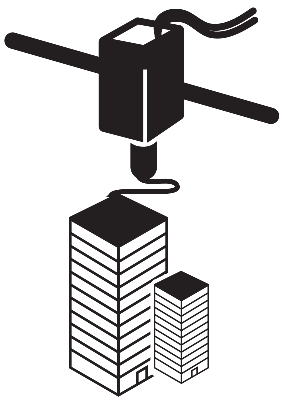

Additive manufacturing of algorithmically form generated nodes for double layer free form structures

Ioannis MIRTSOPOULOS

P2 report | January 2015

Paul de RUITER
Andew BORGART
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Technical Univesity of Delft
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M.Sc. in Building Technology

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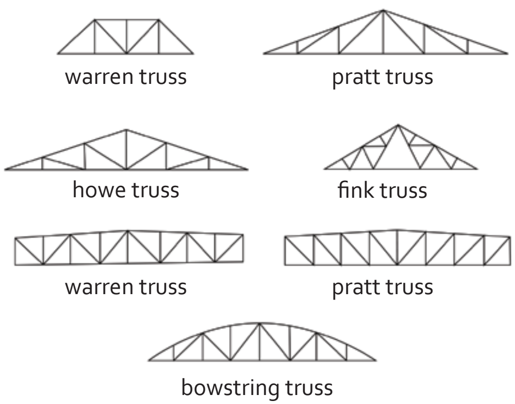
Intro

TOP *Eads bridge, Steel truss-arch bridge, St. Louis, USA* [1874] | ref. [1]
BOTTOM *Forth Rail Bridge, Cantilever truss bridge, Edinburg, Scotland* [1890] | ref. [2]
RIGHT *Typical Planar Trusses* | ref. [3]

Space Frames

Historically, engineers' need to go lightweight and provide the same structural capacity using the least possible material (both for economical and weight purposes), led to the replacement of solid beams by trusses. Trusses are called all structures composed of a number of members pin-connected at their ends to form a stable framework [Chen, Lui, 2005]. Rigidity is ensured by triangulated forms within the borders of the trusses, usually defined by steel or wooden members, designed in a way that they distribute the load better than a series of beams. Typically 50% of the structure is dedicated to supporting itself rather than a load. For a space frame this may be reduced to 30% which means less material is required [Rivas et al, 1999].



The age of steel offered tremendous advances in long-span bridge-building technology and in combination with the truss concept resulted in steel truss-arch bridges and cantilever truss bridges construction in America between 1870 and 1890. These were basically linear applications, but ever since they have been further developed to a third dimension. In fact, many truss structures in nature are three-dimensional (space frames).

Over the last half century steel space structures are gaining rapid acceptance. According to Makowski they are not only attractive but also have greater strength compared with conventional structures and they are more economical to build [Makowski, 1981]. Considering also that architects' ambition of designing column-free large spaces is best answered by space frames, which satisfy the requirements for lightness, economy and speedy construction, easily explains why they have been widely used in many different building types, such as sports arenas, exhibition pavilions, transportation terminal, workshops, warehouses etc. Moreover, from a technical point of view they consist of a large number of simple modular, prefabricated units, often of standard size and shape, all combined into a light but very rigid three dimensional structure.

Space frames are highly statically indeterminate, and their analysis leads to extremely tedious computation if done by hand. Nevertheless, in many cases, such as bridge structures and simple roof systems, the three-dimensional framework can be subdivided into planar components for analysis as planar trusses without seriously compromising the accuracy of the results [Chen, Lui, 2005]. The introduction of computers has radically changed things, since they are capable of analyzing very complex space structures with great accuracy and less time.

Throughout the last century many different types of space frames have been developed (single-, double- or multi-layered) depending on the load magnitude and the span. Some authors define space frames only as double-layer grids, whereas a single-layer space frame that has the form of a curved surface is termed as braced vault, braced dome, or latticed shell [Chen, Lui, 2005]. Engineers do appreciate the great rigidity and stiffness of double layer frames and their ability to resist, large, concentrated or unsymmetrical loading, while architects appreciate their visual beauty and their impressive simplicity [Makowski, 1981]. However, it is important to clarify that double-layer frames can be formed on either a flat or a curved surface and they are used more than single-layered systems as load transfer is mainly done by bending. So for larger spans, the bending stiffness is increased more efficiently by changing to a double-layer system [Chen, Lui, 2005].

Advantages of Space Frames

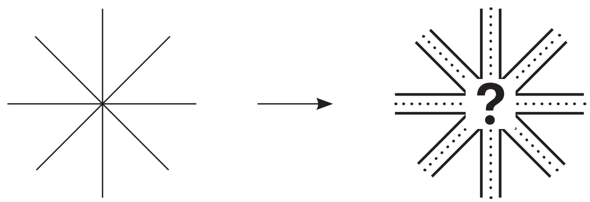
- The most important advantage of a space frame is its lightweight. As already mentioned, all the material is distributed spatially in a way that load transfer mechanism is always axial – tension or compression. So, all material is used to its full extent. Plus most space frames nowadays are constructed with steel or aluminum, which are considerably lightweight.
- All units are usually mass produced. So space frames are built from simple prefabricated units of standard size and shape, which only need to be transferred and assembled on site by semi-skilled labor. Consequently, they can be built at a lower cost.
- Ensure the rigidity of structures transmitting compression or tension in three dimensions.
- Provide design freedom in large span areas.
- Provide column-free spaces.

Beyond the design flexibility and their mechanical benefits, there is also a couple of things to be considered during space frames design. Some of them turn out to be the largest challenges of space frames:

- Given that they consist of linear members, no matter how smooth the curvature of a fee form design might be, the final result will not be a curved interpolated line, but a segmented polyline, that macroscopically will give you the impression of a continuous, perfect and smooth curve.
- Depending on the span of the structure the suitable space frame type needs to be selected and right afterwards, in cases other than single-layer frames, the depth of the grid, the size of cladding and the module size have to be clearly defined while still at an early stage of the design. The size of the module plays a central role to the overall cost, since it defines the number of nodes, and thus the cost and the weight of nodes as well as the assembling or welding labor work. It has to be underlined that the steel consumption covers 15 to 30% of the total [Chen, Lui, 2005]. Thus, it is suggested that grids' dimensioning and depth of structures are determined through structural optimization processes.
- Existing constructional technology has to be considered. Assembling can be done either on the ground or in high position. But, in cases of large scale space frames, the erection might require special methods of construction which need to be pre-thought before lifting the whole structure to the final position.
- The jointing method has to be thought carefully. Jointing does not only affect the weight of structure as described before, but also the overall cost and time of manufacturing and assembling depending on the chosen method. Jointing cost and time are subject to two parameters: **manufacturing**, being lower in cases of mass produced prefabricated and standardized nodes and **labor work for assembling**, if nodes consist of screwing parts, or welding if no nodes are used.

Jointing

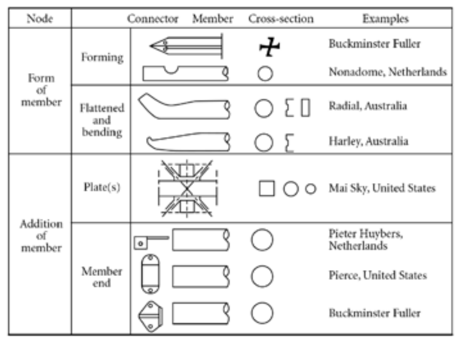
Space frames are characterized by multiple intersections or nodes or joints as they are usually called. Regardless of the section type of members used, the geometry of them requires a special node where all the meeting members can be jointed.



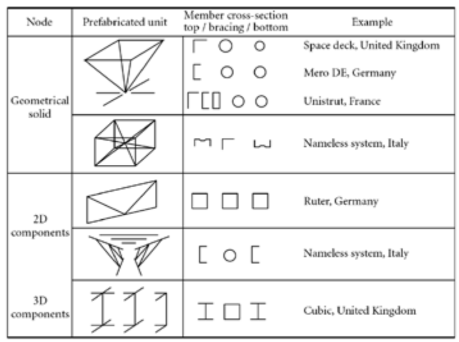
Alternatively, without extra nodes utilized, members can be welded resulting in – theoretically - rigid or hinged joints, as in engineering practice there are no absolutely rigid or hinged joints [Chen, Lui, 2005]. Jointing is affected by the shape of the members. Tubular space frames are highly efficient systems from a structural point of view [Rivas et al, 1999]. Their structural efficiency is explained as their section is always symmetrical to the load case regardless of its vector's direction. Similarly to all sections though, jointing is a challenge.

Even if the nodes' weight is only one third of the overall weight of space frames, which could be eliminated by welding all members, jointing occupies a major portion of the structure cost, either as manufacturing and bolting of nodes or as welding activity or as special mechanical connectors application. Jointing mechanism is the most important part of a space frame, or a planar structure, and must comply with specific requirements. It must be strong and stiff, simple structurally and mechanically and easily manufactured when talking about node joints. The cost of their production affects the cost of the overall structure and thus many node jointing systems have been mass produced in the past decades, emphasizing in low cost, standardization and mass applicability. Worldwide there are over 250 different types of jointing systems suggested or used in practice, manufactured by over than 50 commercial firms specializing in jointing systems for space frames. Unfortunately, many of these systems have not been proven to be successful due to the complexity of the connecting method [Chen, Lui, 2005]. The following table shows a comprehensive list of the jointing systems all over the world.

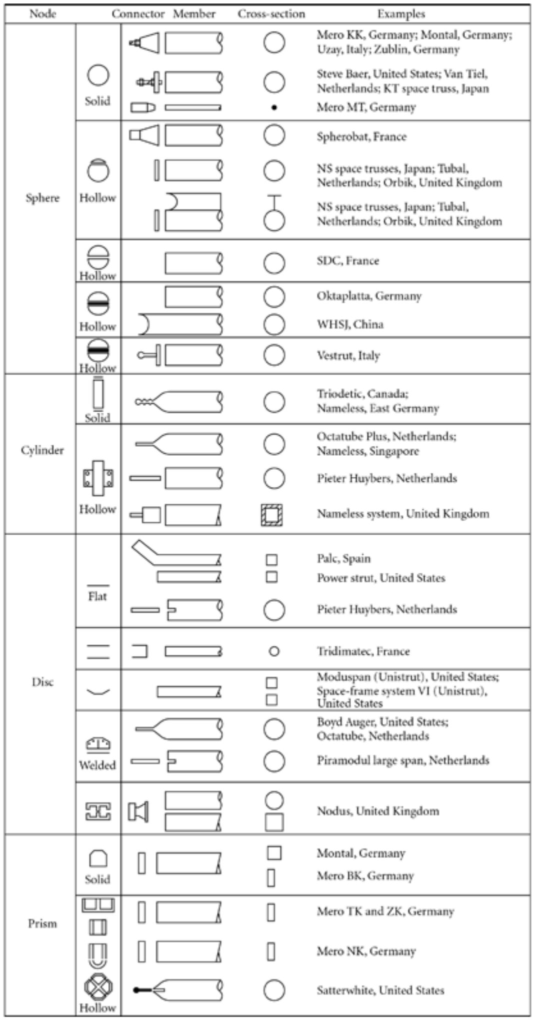
Connecting types without a node



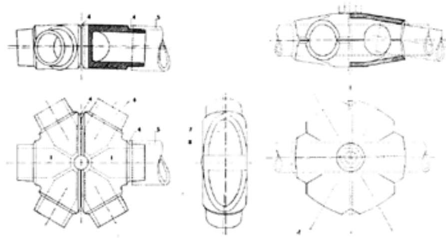
Connecting types with prefabricated units



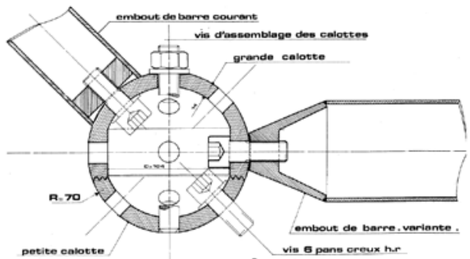
Connecting types with a node



Node		Connector	Member	Cross-section	Examples
Sphere	Solid				Mero KK, Germany; Montal, Germany; Uzay, Italy; Zublin, Germany
					Steve Baer, United States; Van Tiel, Netherlands; KT space truss, Japan
					Mero MT, Germany
	Hollow				Spherobat, France
					NS space trusses, Japan; Tubal, Netherlands; Orbik, United Kingdom
					NS space trusses, Japan; Tubal, Netherlands; Orbik, United Kingdom
	Hollow				SDC, France
	Hollow				Oktaplatta, Germany
					WHSJ, China
	Hollow				Vestrut, Italy
Cylinder	Solid				Triodetic, Canada; Nameless, East Germany
	Hollow				Octatube Plus, Netherlands; Nameless, Singapore
					Pieter Huybers, Netherlands
					Nameless system, United Kingdom
Disc	Flat				Palc, Spain
					Power strut, United States
					Pieter Huybers, Netherlands
					Tridimatec, France
					Moduspan (Unistrut), United States; Space-frame system VI (Unistrut), United States
	Welded				Boyd Auger, United States; Octatube, Netherlands
					Piramodul large span, Netherlands
					Nodus, United Kingdom
Prism	Solid				Montal, Germany
					Mero BK, Germany
					Mero TK and ZK, Germany
					Mero NK, Germany
	Hollow				Satterwhite, United States



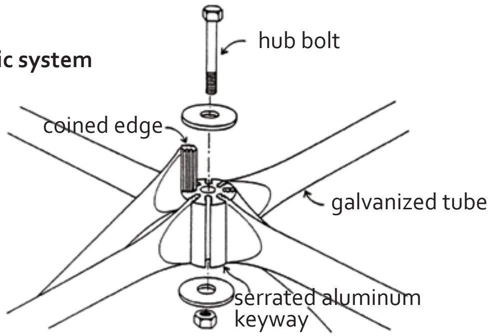
SDC node



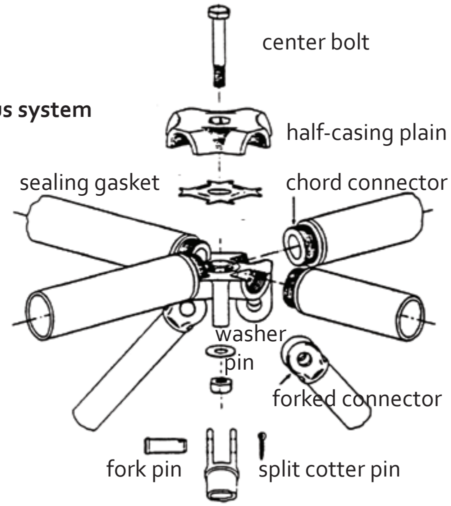
Spherobat node

LEFT *Jointing systems all over the world* | ref. [4]
MIDDLE *Node systems patented by Stephane Du Chateau* | ref. [5]
RIGHT *MERO Nodes drawings* | ref. [6]

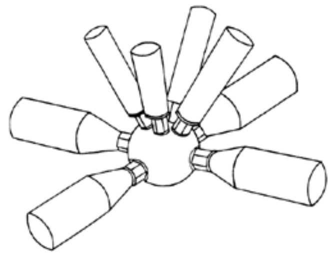
Triodesic system

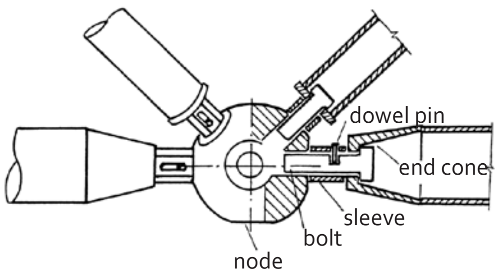


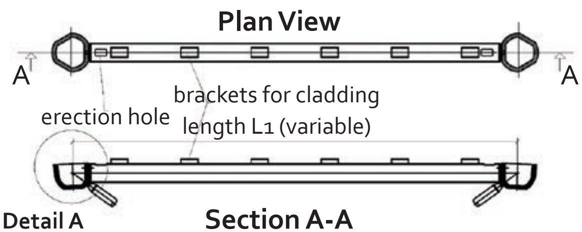
Nodus system

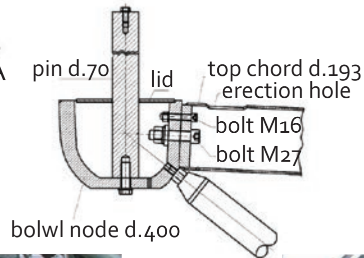


As already implied, all the above presented jointing systems are industrialized, mass produced solutions applicable to simple space frames. The challenge is getting greater once members of free form space frames need to be jointed. Some of the above mentioned industries are also occupied with special connectors manufacturing for free form designs. Even MERO manufacturer, which has been proved to be extremely popular manufacturing standardized nodes for grid space frames, has dealt with special connectors for special projects. Some MERO or other manufacturers' examples are following:



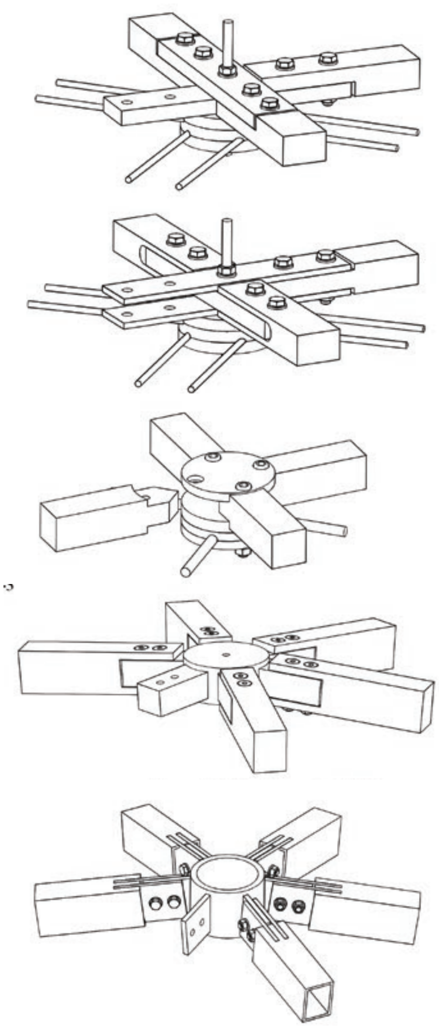






TOP *Eden Project, Cornwall, UK* [2000] | ref. [7]
MIDDLE *Bowl Node System drawings* | ref. [8]
BOTTOM *Bowl Nodes in Eden Project* | ref. [9]

RIGHT *Spline Connectors developed by different industries* | ref. [10]



Double Layer Free-Form Structures

Eden Project
For the nodes of this geodesic domes project, a new node was designed (Bowl Node System). Similarly to the famous classic Ball Node System Its geometry is spherical but hollow with a wall thickness of 40mm and 400mm diameter for the specific project. 1100 uniquely numbered such nodes were manufactured using computer aided machines in MERO workshop close to Wuerzburg in Germany.

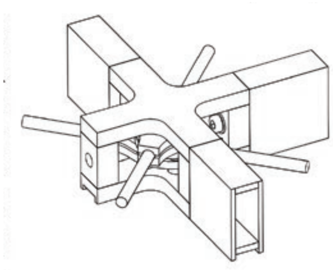
Other double layer free-form structures were Bowl Node System was used: Stockholm Globe Arena, Singapore Arts Center

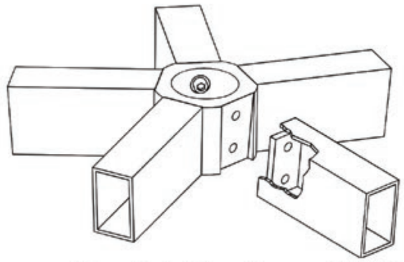
Single Layer Free-Form Structures

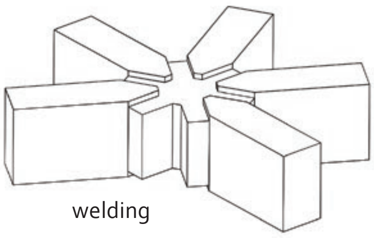
Node connectors for single layer structures can be divided in two categories: spline connectors and end-face connectors.

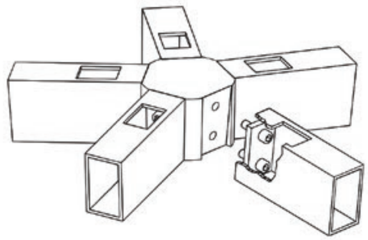
Spline connectors are characterized by the following:

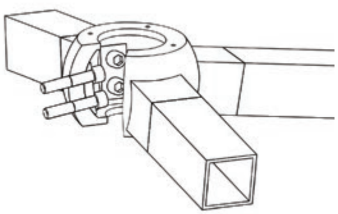
- The contact surface between the node and the connected structural member runs along splice plates in the longitudinal axis of the member
- The fixing can be realized as a bolted splice with shear-stressed bolts or by welding.

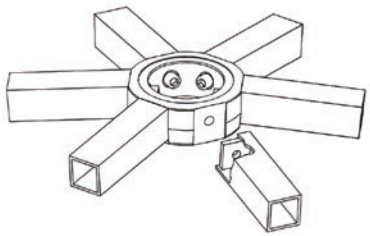




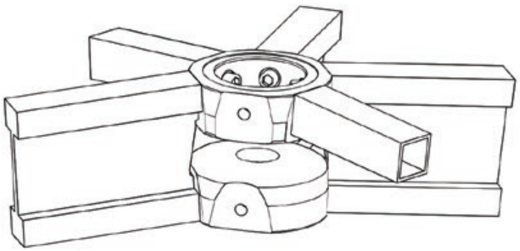


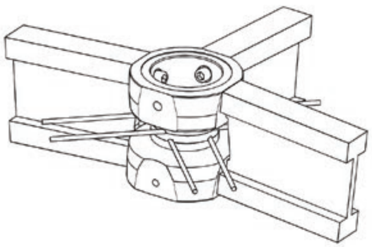






LEFT *End-Face Connectors developed by different industries* | ref. [11]
MIDDLE *End-Face Connectors developed by MERO* | ref. [12]
RIGHT *Nodes manufactured for New Fair in Milan space frame* | ref. [13]





End-face connectors are characterized by the following:

- The contact surface between the node and the end-face of the connected structural member is transverse to the longitudinal axis of the structural member.
- The connection can be realized as an end-plate connection with tension-stressed bolts or by welding.

MERO industry from its side, in 1994 published a series of end face connectors for single layer free form structures along with the Bowl Node System which was called “MERO Plus”. Similarly to Bowl Node System, the end face connector launched is made from a hollow cylinder with openings, either on both ends or at the top, or no openings at all, and each structural member is connected to the node cylinder by two bolts.

A few years later [2005] the same node was further developed for the needs of the roofs over the Central Axis and the Service Center of the New Fair in Milan, Italy. Both roofs are free-form reticulated structures. The roof over the Central Axis has a length of approximately 1300m and a width of 32m and consists of 16000 nodes and 41000 structural members. The structural members are connected to both nodes by two bolts or welding.

TOP *Welded Node Connections in King Cross Station, London* [2005] | ref. [14]

One method that is also widely used for jointing is welding. In that case, cost of labor work is quite high. One famous example of welded jointing is found at the new roof structure of King Cross station in London, completed in 2012.

1. Research Plan

Problem Definition

The starting point of this research is to simplify the jointing systems of large span free form space frames nodes. As described before, jointing has been the biggest challenge of a space frame and the most expensive part of these structures, especially if special connectors need to be designed, manufactured and applied. The drawback of all the above systems, applicable either to single- or double-layer free form structures, is that in most cases they are too complicated consisting of multiple elements and usually bolts need to be used. Moreover, being mass produced, they usually use more material than would probably be needed so that they can be applicable to more cases. Consequently more material is used, which rises both the cost and the weight of the structure. Last but not least, assembling is a big issue. No matter which jointing is chosen, using or not some node, there is a lot of labor work that needs to be done. The more complexity a node has the more time it will need to be assembled, placing all bolts in place applying the needed amount of torque. Thus the overall cost is rised by more than one factors.

Out of all the processes described, MERO systems assembling (pin-joint connections), used at the classic Ball Node System, is proven to be the simplest one, demanding to screw only the members on the node but no more elements. This simplicity explains their acceptance by builders, their extensive usage in different applications and the launch of nodes assembled with the same principle by many other manufacturers.

"...but he [Stephane Du Chateau] had always two main conerns in head: the node and the industrialization process. All people who were involved in spatial structures design, know that the main question to solve is the node design"[1]

[1] *Motro, 2013, 2*

It is crucial to keep in mind that manufacturing options affect in their way the design and the cost of nodes. Being the result of a production line, their manufacturing needs to be fast and cheap. Quality reduction cannot be an option, so keeping forms as simple as possible from a manufacturing point of view and flexible for multiple applications can contribute towards this direction. Furthermore, their structural capacity is identical for all the nodes of a production line even if this is not needed, depending on their location. This means that material use could be eliminated, manufacturing optimized nodes per every application. Then complexity would not be a problem. First, complex forms would not be an obstacle, provided that there is manufacturing technological knowledge and secondly, nodes would not be part of a complicated manufacturing process.

Additive manufacturing benefits can be summarized in the capability of fabricating forms of large complexity in small amount. Considering that additive manufacturing does not have to be part of a complicated process to be cost effective and every product's manufacturing can be unique within the constraints of the manufacturing process (potentially only slight adjustments need to be made to the machine setup), it can be a solution for highly individualized nodes, optimized to carry the load applied to the specific location, optimizing material use and reducing the cost of additive manufacturing.

But still the most appropriate additive manufacturing technique has to be found. As nodes are structural components carrying loads, the chosen manufacturing process (technique and material) should not only be equally fast and cheap to investment cast or combination of casting and machining used now, but above all structurally approved, so that the final product will still be able to distribute the loads. Then the question that rises is; which are the cost and the time of manufacturing. Recognizing as part of this research the structural performance of additively manufactured nodes, time and cost of manufacturing are not taken into account. Nevertheless consider that complicated jointing systems do require a lot of assembling time,a process costing labor work.

The additive manufacturing process is selected to cope with the form complexity of the individual optimized nodes. The structural performance of different techniques and materials need to be tested. Nevertheless, the materials that are going to be tested along with these techniques are not going to be neither metal alloys nor non conventional. When taking a closer look to the body of knowledge for the mechanical properties of additive manufactured products, it becomes clear that huge steps need to be taken before they are applied on buildings or structures, as there are almost no mechanical properties registered.

To tackle with this problem, one phase of this research – the experimental - focuses on which of the additive manufacturing techniques in combination with which materials are the most appropriate ones to manufacture nodes. Specific material properties also need to be considered. Existing data will be taken into account but the body of knowledge lacks in many material's properties.

At the last stage, all knowledge acquired will be used as input to an algorithm capable of generating form optimized nodes according to the loads of a structure.

All the above can be summarized into the following two main problems:

-Can form generated individualized nodes produced with additive manufacturing techniques reduce the complexity of jointing for double layer free form structures?

-Which additive manufacturing technique in combination with which material can be used to manufacture these nodes, considering at the same time their structural capacity within the limitation of the chosen manufacturing process

Additional things to consider:

- The assembling method of these nodes will be adopted by the classic MERO system (pin-joint connection), which is the simplest one.
- The source material should be thoughtfully selected, in a way that load transferring steel shafts can be attached on the new node
- Size in manufacturing is of utmost importance. Thus, the overall geometry of the generated node should comply with the maximum manufacturing dimensions provided by machines specifications, as techniques are not always applicable to all scales.
- Material properties have to comply with conditions applicable to both indoor and outdoor environments
- High levels of accuracy are demanded both in calculations and manufacturing later on

Further subdivision of the problem:
The two main problems given before can be further divided into a list of sub-problems and all together they finally form the overall problem, clearly and tangibly.

- Pin-joint connection principle is based on threaded nodes, so which production technique offers enough accuracy to manufacture threads and which material can be used for threads?
- What is the maximum number of shafts applied to the nodes?
- If the optimum additive manufacturing technique is powder based, how can excess material be released from the interior of the node?
- How anisotropy can be avoided, given that additive manufacturing is based on layer by layer production?

1. Research Plan

Scope of the Research

One part of this research deals with the creation of an algorithm that will be able to form generate optimized nodes for free form surface structures which later on will be fabricated using additive manufacturing techniques. The algorithm will be taking as input a free form double-layer structure and based on generic rules related to mechanics and 3D printing capabilities will be generating an individualized node, for every intersection, capable of carrying the loads of its location. Additive manufacturing limitations will also be considered in this generative algorithm, indicated to the user as manufacturing incapability. Unfortunately, nowadays there is limited or no knowledge on the mechanical properties of additive manufacturing techniques and materials. It thus becomes crucial to execute physical tests. The structural behavior will be tested using specimens, manufactured with different additive manufacturing techniques and materials, and studying their failure modes. This second part - the experimental - will allow me to investigate the flaws of each additive manufacturing technique, drop the options that do not have any structural potential, create and import new material databases in finite element analysis software to be used as an input for the generative algorithm.

Research Question & Objectives

With the boundaries of the research area set, the steps which have been taken within the scope of the research can be put under three main objectives:

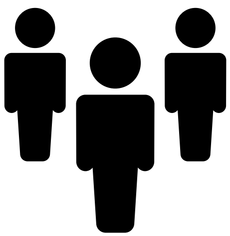
- Algorithmic nodes generation using computational tools, optimized for least material usage and high structural performance based on generic rules defined by mechanics and 3D printing possibilities and limitations.
- Find the optimum additive manufacturing process in combination with material that can have mechanical and material properties capable to serve large span structures nodes' needs
- Acquire all the needed mechanical properties of the selected process and material and use them as input in finite element analysis software, similarly to concrete, steel and other predefined material options given

From the above mentioned objectives the research question is logically formed as follows:

How is it feasible to additively manufacture algorithmically form generated nodes for space structures with pin-joint connections?

Social Relevance of the Research

The outcome of this research - a user friendly algorithmic form generator - will be a helpful and relieving solution for architects and engineers, who are still struggling for optimum nodes design but still mass produced. This tool will allow even more freedom of design and will definitely broaden form finding opportunities. Of course, such a goal would be impossible to be reached without the integration of additive manufacturing techniques' benefits through the production phase. The specimen testings will give an indication of AM materials structural performance and will trigger further investigation and enhancement of their structural capacity. As for the creation of "new material" databases imported in finite element analysis software, they will allow optimization of additively manufactured products. Finally additively manufactured materials will be considered equivalent to other materials, coming together with properties agentas, expanding the material portfolio of designers, architects, engineers, builders and manufacturers, taking advantage of complex form manufacturing capability.

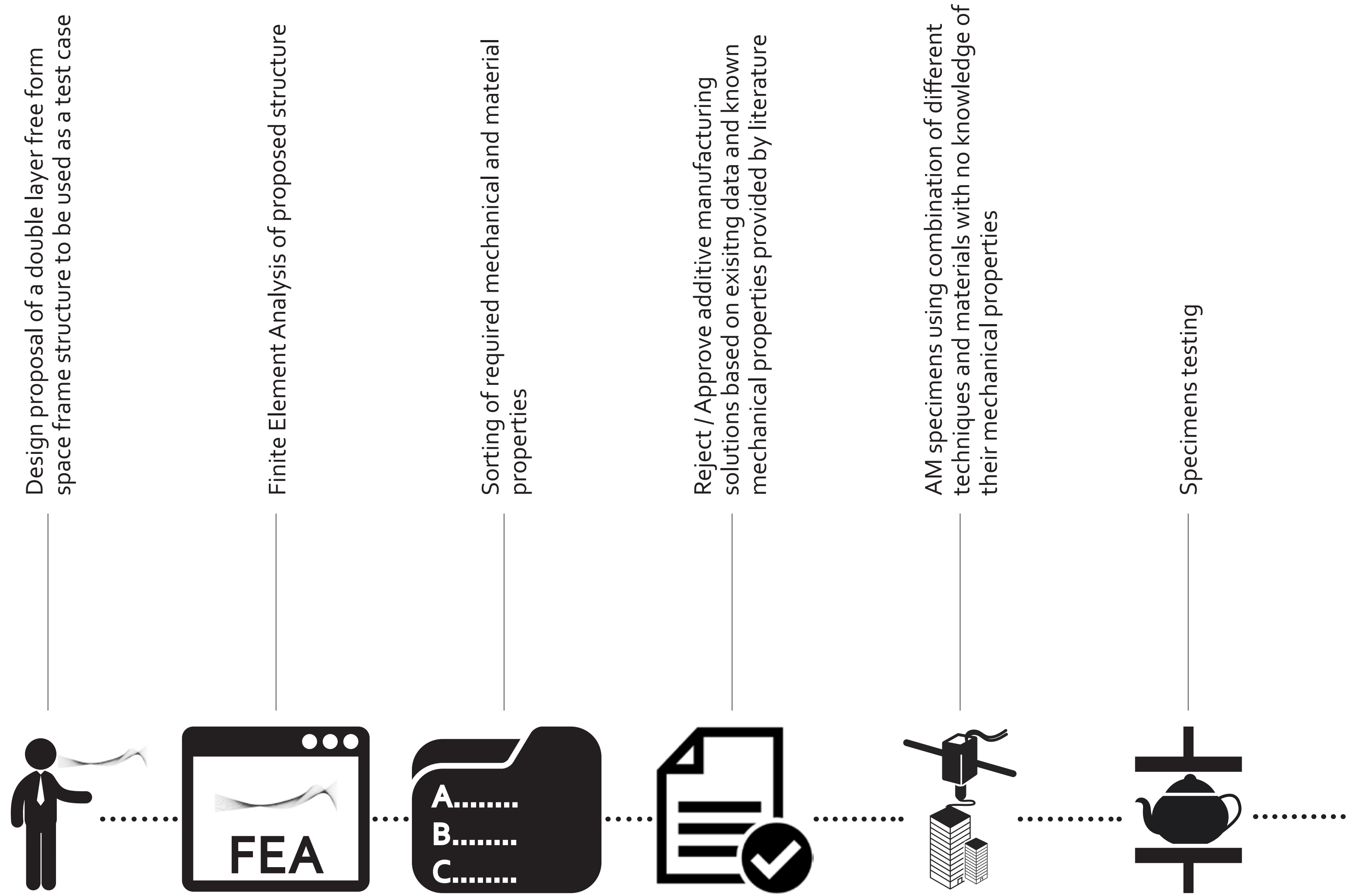


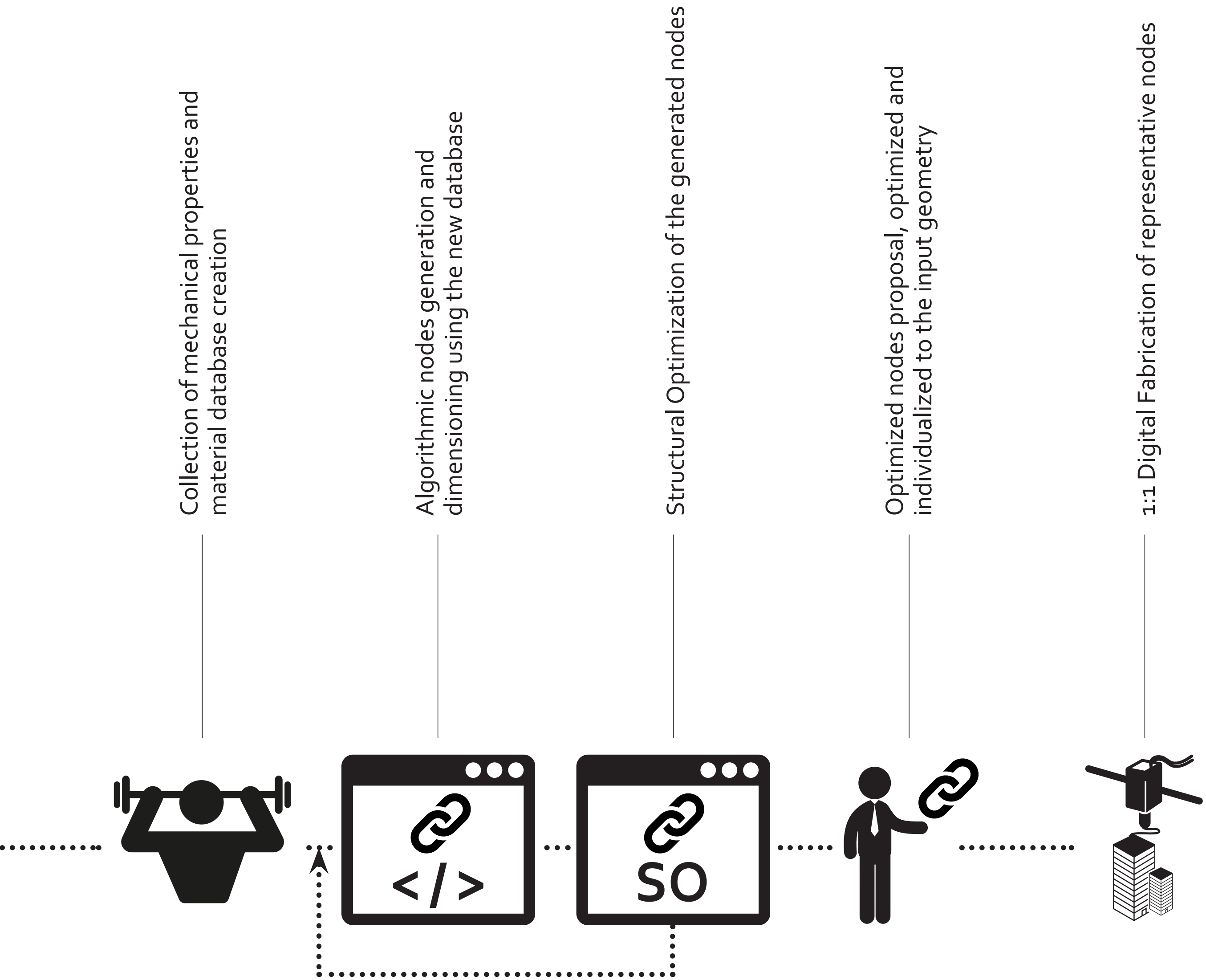
Research Methodology

In order to prove its concept, this research starts with a design proposal of a large span double-layer free form structure which is going to be the test case. This proposal is going to be analysed using finite element method for ultimate limit state loadcase, whereas the user will be able to change both the safety factors and the wind and/or snow load. Upon completion, I will be aware of the stresses along every member and node for the specific span and design, and I will be able to quantify my mechanical properties requirements along with the material ones. Emphasis will be given to 5 representative point nodes. Having a clear perspective on my requirements, I will reject or approve manufacturing solutions (combination of techniques and materials), serving the specific needs, based on existing data and known mechanical properties provided by literature. The gap of knowledge regarding the mechanical properties of some materials is going to be bridged by fabricating specimens and testing them. Finally, I will be aware of the mechanical properties of a range of additively manufactured materials and the optimum ones, according to my needs, will be chosen to create new material databases to be used in finite element analysis software. These new databases will be used as input to an algorithmic node generation process, affecting the dimensioning of nodes. Out of the generative algorithm, whose generic rules are defined by mechanics and 3D printing possibilities and limitations, it will be possible to get as output the optimized and structurally efficient nodes for the structure used as input. Once the generative process is completed, the 5 representative points' nodes will be fabricated in 1:1 scale.

1. Research Plan

Research Methology




Collection of mechanical properties and material database creation
Algorithmic nodes generation and dimensioning using the new database
Structural Optimization of the generated nodes
Optimized nodes proposal, optimized and individualized to the input geometry
1:1 Digital Fabrication of representative nodes
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SO

2. Manufacturing

Digital Design / Digital Fabrication [CAD/CAM]

The built environment and architecture are concerned with two core activities: design and making. The development of numerous CAD and other software packages has offered freedom of design and complexity that could never be conceived before. As far as design in concerned, Toni Kotnik describes that the integration of computers as tools into the design process can help define elements of a computable function as design tools [Kotnik, 2010]. These functions stand for representation purposes [computerization], algorithmic and parametric design. The complexity of forms is usually impossible to be materialized applying traditional techniques and that is how proves that the influence of digital design on fabrication is great too. These changes in design process have evidenced the increased need of multidisciplinary but also computational approaches throughout the whole process, from conceptualization and analysis, to fabrication and manufacturing, and finally managed to integrate technologies like CAD/CAM [Computer Aided Design/Computer Aided Manufacture], CNC [Computer Numerically Controlled] milling and Rapid Prototyping [RP] in it. However, the materialization of a design is not a one-way street, applying unique techniques, but instead is a unique practice of making, often resulting in non-linear processes of working [Dunn, 2012]. Although most of these techniques are new in architecture, they have been used for other applications for more than 50 years now. And yet "*as the process of making drawings steadily shifted from being analog to digital, the design of buildings did not really reflect the change [...]. Buildings looked pretty much the same*"[2] until building industry fully adopted digital fabrication techniques.

Given all the challenges that digital fabrication hides, one logically wonders why the necessity to use it. Although traditional manufacturing allows mass production and is economically viable assembling standard components, digital fabrication has given new potentials to the process of manufacturing, as it allows:

- fluid workflow from concept to realization [file-to-factory]
- vast material explorations
- individualized components [mass customization]

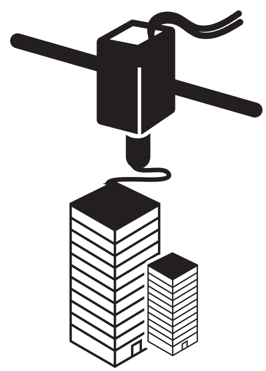
Nowadays, the manufacturing industry involves one, or a combination of four basic approaches:
Cutting: the process of trimming material e.g laser cutting, plasma arc, water jet
Additive: the process of adding material to build up the product
Formative: the process of forming the product through the use of moulds for example
Subtractive: the process of forming the product by removing material through cutting, milling or grinding

Throughout this research the focus of manufacturing has been on additive manufacturing processes because of their advantages.

[2] *Iwamoto, 2009, 3*

Additive Manufacturing

Additive Manufacturing, derived from Rapid Prototyping, has been investigated and developed for more than 30 years and includes three different categories of technologies depending on the source material used: liquid, powder and solid based technologies [Hopkinson et al, 2006], which are all used in manufacturing free form objects. Additive manufacturing – or 3D printing as it has predominated – is defined by American Society for Testing and Materials as the *"process of joining materials to make objects from 3D model data, usually layer upon layer"*[3]. The term additive manufacturing is used in preference to "layer" manufacturing as it is likely that some future Rapid Manufacturing systems will operate in a multi-axis fashion as opposed to the current layer-wise manufacturing encountered in today's rapid prototyping [Hopkinson et al, 2006]. Its greatest advantage as a manufacturing technique is the **capability of fabricating designs of any complexity**, while the greatest disadvantage is **the change of structural behavior along different axes due to anisotropy**.



[3] *Lim S., Buswel R.A., Le T.T., Austin S.A., Gibb A.G.F., Thorpe T., 2012, 262*

2. Manufacturing

Additive Manufacturing

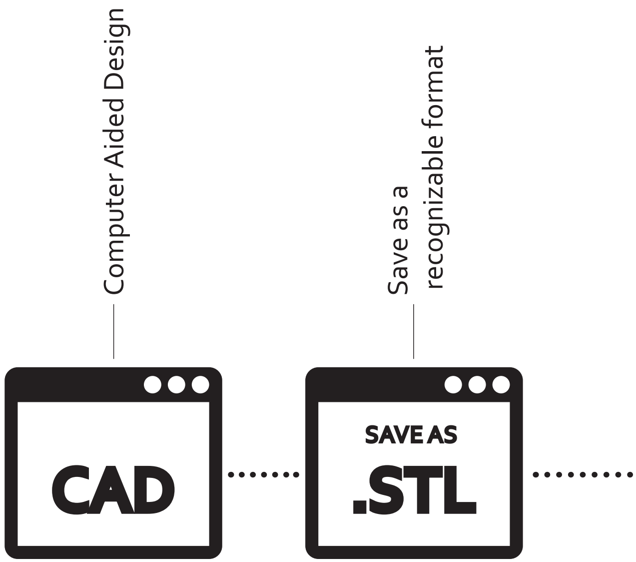
Workflow

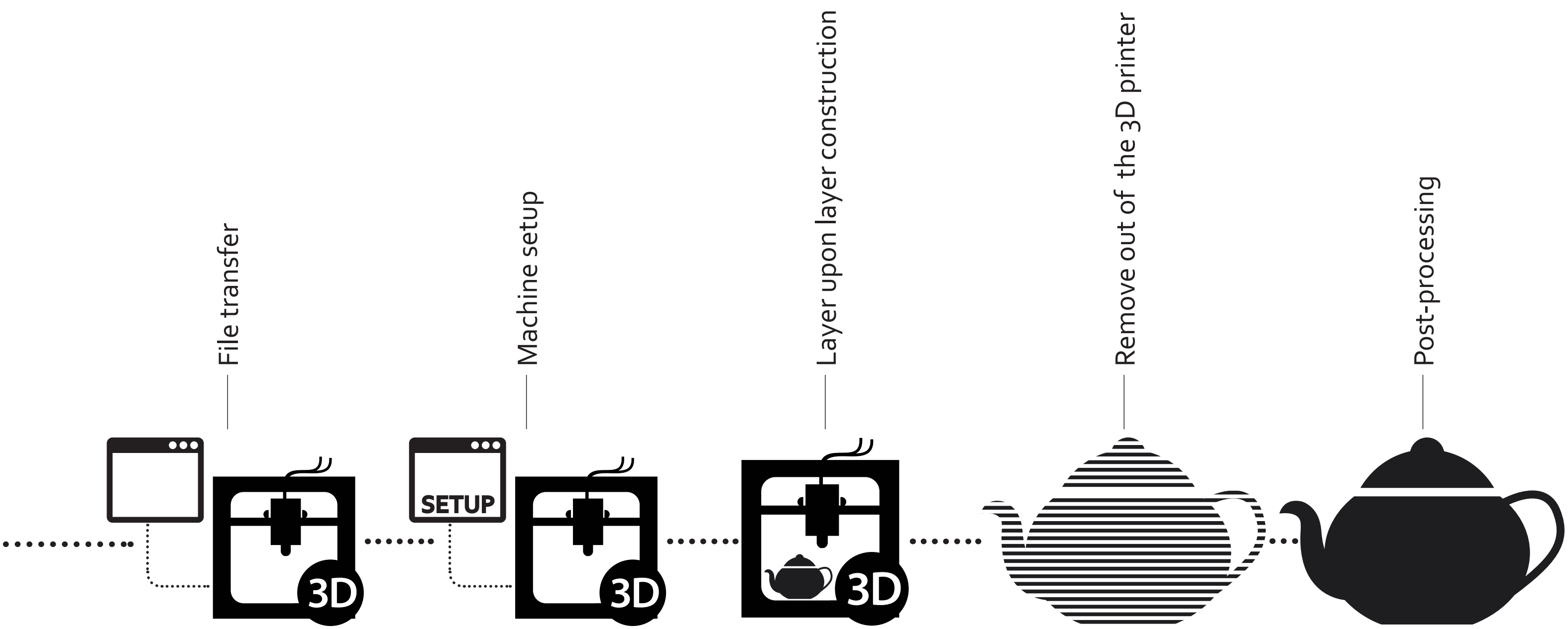
"...this emerging technologically enabled transformation of the building industry in the "digital" age has led to a much greater integration of "mechanical" age processes and techniques into conceptual building design" [4]

When it comes to digital fabrication there are plenty of different techniques applicable to different occasions incorporating their own benefits and disadvantages. Regardless of the technique, the process in order to bring a CAD model into materialization includes a couple of steps to be completed including the collection of digital data as an input from design software, which is transformed into a format recognizable by CAD/CAM machines. More analytically, focusing on additive manufacturing techniques, each layer of the slice by slice manufacturing constitutes a thin cross-section of the object and derives from the original CAD file, which is either a solid or a surface representation. Once the 3D model is ready it has to be exported into a .STL format, which in fact describes the external closed surfaces of the CAD model and serves the basis for calculation of the slices. Then file is transferred to the machine, where manipulations like scaling, positioning and orientation for building take place. Afterwards, the machine is set up. That is the process where support material is enabled, temperature values, manufacturing speed and layer thickness etc are chosen, so that the G-code can be generated. Once the G-code is ready the building process can be started by the operator who will only getting back regularlly for supervision. After the end of building, support material –if there is any - is either removed or put into dissolving liquids as part of the post-process, which might also include painting, polishing, finishing etc. Finally, the new product is ready to be used.

[4] *Kolarevic, Klingers, 2008, 7*

Thus adoption of CAM technologies does not only mean inclusion of digital fabrication techniques in the design process, but designers need to be aware of how these translation processes work, so that they can fully take advantage of the machines' capabilities [Dunn, 2012].

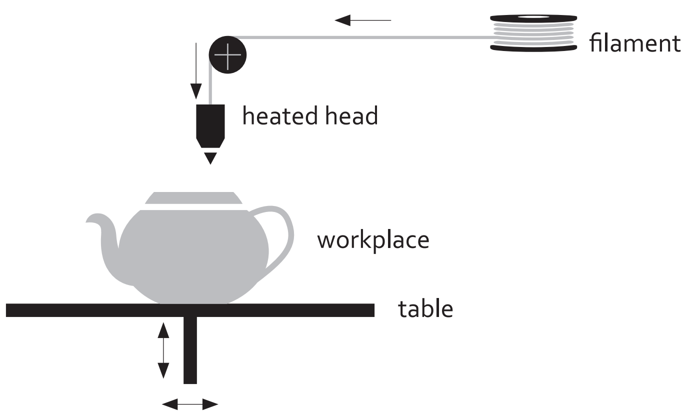


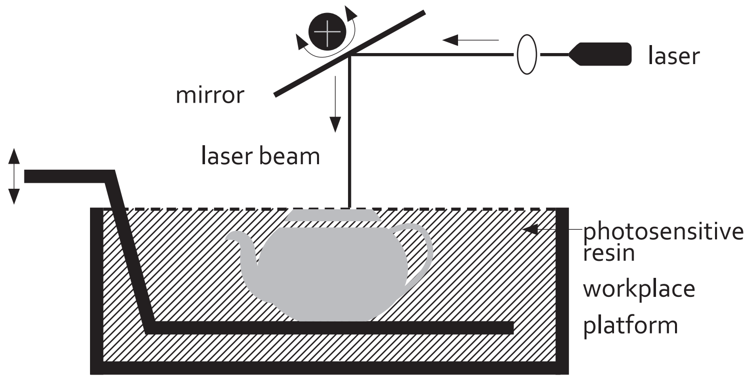

File transfer
Machine setup
Layer upon layer construction
Remove out of the 3D printer
Post-processing
SETUP
3D
3D
3D

Additive Manufacturing
Techniques

Fused Modeling Deposition [FDM]
It was first launched by Stratasys in 1992. It builds parts by extruding melted material [usually a thermoplastic, wax or nylon material] through a nozzle [head] capable of moving along X and Y axes [Hopkinson et al, 2006]. Material used to build the form is deposited from a different nozzle to the one that deposits supporting material. Support material is deposited simultaneously with the build one, resulting in an object that has to be post-processed before it serves its purpose. The build material usually used is ABS, while the support material is PLA, which is water dissolvable. Other materials are possible to be used, provided that they are thermoplastic. The simplicity of this process is the reason that it has been adopted by the majority of the home 3D printers, although it is relatively slow process. Its greatest disadvantage is that FDM printers are supplied with **polymers**, which do not have high structural performance and are susceptible to weather conditions.

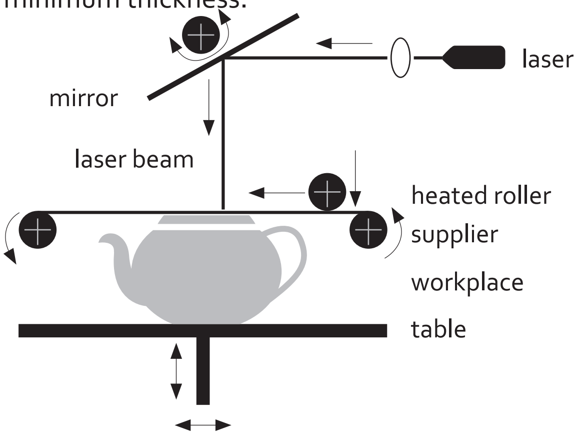
Stereolithography [STL]
It uses polymerization to build models. A photocurable resin in liquid form is placed in a tube and an ultraviolet (UV) laser is exploited to initiate a curing reaction in the resin. The laser is driven according to the CAD file data that is supplied with, curing the resin which is later solidified on to the platform. The platform then is lowered, usually by 100μm, and a fresh layer of liquid resin is deposited over the previous layer [Hopkinson et al, 2006]. This process is slow, precise, relatively expensive and usually demands supporting material. The models on the other hand are quite hard, tough and slightly transparent. Stereolithography machines are compact and considered to be environment-friendly, and the process itself, though relatively expensive, is widely used [Schodek et al, 2005].





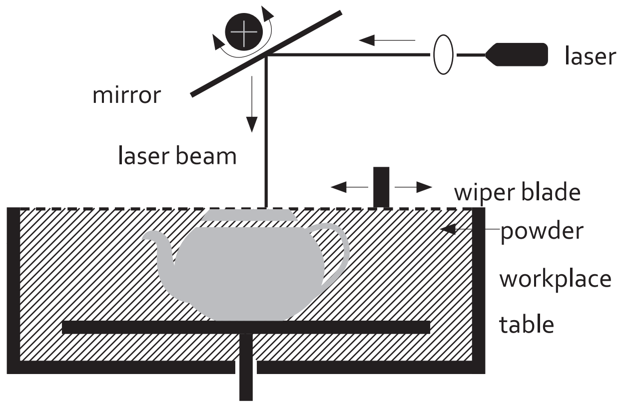
Laminated Object Manufacturing [LOM]

It belongs to the sheet stacking technologies and its function is based on the idea of cutting and stacking two dimensional sheets of **various materials** with cardboard being the most famous one. The disadvantage of this process is that when it comes to cutting complex geometries with thin walls, post-processing is difficult, time-consuming and can damage the part [Hopkinson et al, 2006]. However, there have some impressive paradigms of metal sheets bonded together by low-temperature ultrasonic diffusion. The machine used is quite simple. A roller supplies the cutting machine with paper or sheet material to the platform, where the cutting process takes place. Then the shape is dropped below the material roll, and the roll is advanced. A heated or pressurized roller deposits a new sheet on top of the previous one and the process is repeated until the desired solid object is completed [Schodek et al, 2005]. The main benefit of this process is that there are no limitations and restrains, especially regarding maximum size and minimum thickness.



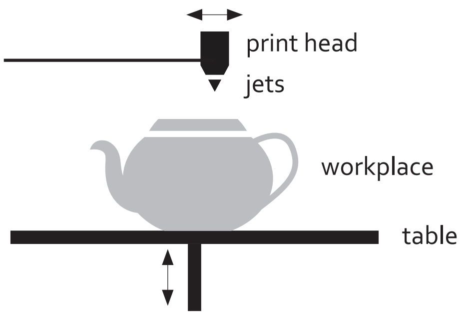
Selective Laser Sintering [SLS]

It is quite similar to stereolithography, but the powder source material [usually **metal** or **ceramic** but also **polymer** powder] is sintered or melted by a laser that selectively scans the surface of a powder bed to and through a heating process create a two-dimensional solid shape [Hopkinson et al, 2006]. Like in stereolithograpy, each layer's thickness is approximately 100μm. The un-fused powder acts as a supporting material which obviates the need for support removal during post-processing. The powder bed is heated prior to laser scanning to bring the temperature of the powder up to a temperature that is typically a few degrees Celsius below the sintering temperature. This pre-heating helps the process by reducing thermal gradients between sintered and non-sintered powder and reduces the energy required by the laser to sinter the powder. Research has shown that a high sintering rate is possible and results in minimal shrinkage and good edge definition but poor mechanical properties [Hopkinson et al, 2006].



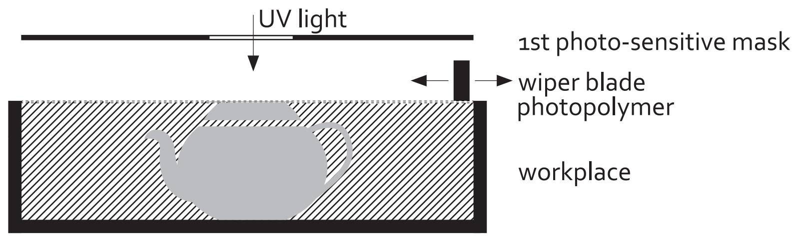
Ink-jet Based 3D Printing

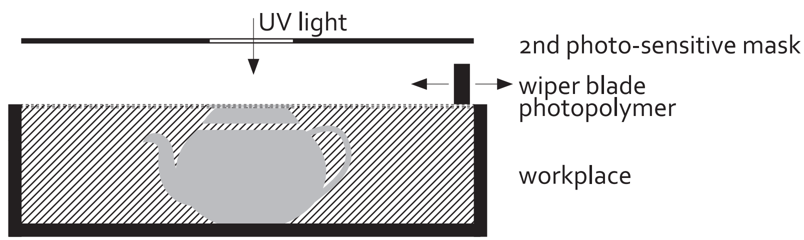
These methods are applied to powder based techniques. One of the most famous techniques works in layers similarly to SLS manufacturing process. The powder lies in big volume tank and a modified ink-jet print head passes over it, releasing glue rather than ink. The glue binds powder that it contacts, leaving the rest of the powder to support the object as it is produced [Hopkinson et al, 2006]. After building process is finished, the unused powder is removed by compressed air and the model is hardened applying hot wax, glue or resin. The most common powders used are **starch** and **gypsum**, making the process one of the cheapest ones. Unfortunately powder-based ink-jetting printing machines, which are compact themselves, have to be combined with more machines, like vacuum and waxing system, and infrastructure such as good ventilation in the lab, to deal with the challenge of powder management, as particles have the tendency to get into the air.



Solid Ground Curing [SGC)]

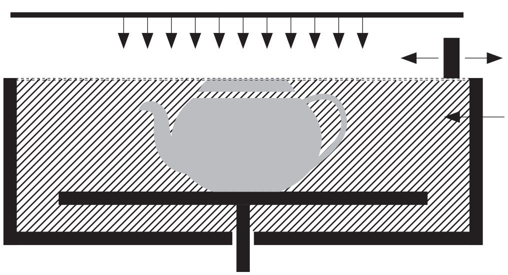
It utilizes photolithography, using photomasks rather than a pinpoint laser to develop the liquid polymer. SGC machines use an eraseable mask produced with an electrostatic toner to control ultraviolet light. The light selectively cures the material and uncured metal is removed to be replaced with a water-soluble wax. Once the wax is flat is entire surface is milled lat and the process begins again using a new mask [Hopkinson et al, 2006]. One of SGC's benefits is that can build multiple parts rapidly firstly because of the large surface area that can be cured at the same time and secondly because the building time of one layer is not dependent on the size of the cross section.

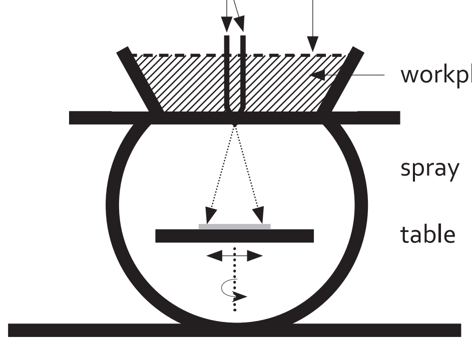




Selective Masking Sintering [SMS]
It involves printing a mask of infrared radiation reflecting material on to a glass sheet and placing the sheet over a powder bed. Infrared radiation is then applied to sinter the powder directly below. This process eliminates the requirement for a laser and in instances where a significant portion of the surface needs to be sintered this should dramatically reduce processing times when compared with selective laser sintering. It is claimed that each layer can be fully processed in 10-20 seconds and that the use of a mask in place of a laser ensures that build times are easy to predict and independent of part volume [Hopkinson et al, 2006]. Consequently, this approach is epxected to have maximum benefits when being used for Rapid Manufacturing in high volumes.

Fused Metal (droplets) Deposition [FMD]
It is a technique applicable to metals fabrication. The metal or alloy is melted in a crucible located on top of a spray chamber. As it exits the crucible it is atomized using an inert gas (either nitrogen or argon). The droplets are caused to impinge and consolidate on a platform and gradually build up a layer of dense solid metal. The final product is characterized by uniform, fine grains and freedom from macro-segregation, while its mechanical properties are isotropic and comparable to products of conventional processes [CES EduPack 2014].





Electron Beam Melting [EBM]

The process uses a similar approach to selective laser sintering but replaces a laser with an electron beam. Melting is produced by the heat of a focused beam high velocity electrons. The kinetic energy of the electrons is converted into heat when it hits the work piece, which has to be contained in a vacuum chamber [CES EduPack 2014]. This substitution of laser beam has interesting implications. Firstly, the electron beam may be directed by changing the electromagnetic field through which it passes. This eliminates the need for scanning mirrors and can significantly increase scanning speed. Secondly, the power developed by the electron beam is very high, allowing the process to fully melt a wide range of metals including titanium alloy using a very fast scanning rate. However, the process is limited to conductive materials and surfaces, as with many other layer-based processes, often require extensive finishing [Hopkinson et al, 2006].

Direct Metal Laser Sintering

It is a variation of selective laser sintering that can produce metal parts without the need for a binder coating and the subsequent processing that is required. The process involves either melting or liquid phase sintering of the metal powder, which usually is a mixture of various components having different melting points [Hopkinson et al, 2006].

The list with the additive manufacturing techniques can go long including many experimental approaches as a result of research conducted in universities. However, they are still under development, usually with many flaws (poor consolidation) that need to be fixed and they are not commercialized. This means that even they would serve our purpose and research objectives they are not available to the public. Likely, digital fabrication field, lately, meets massive evolution promising impressive results in quite short period of time.

3. Design

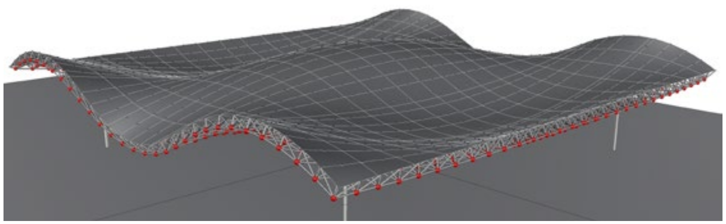
Purpose

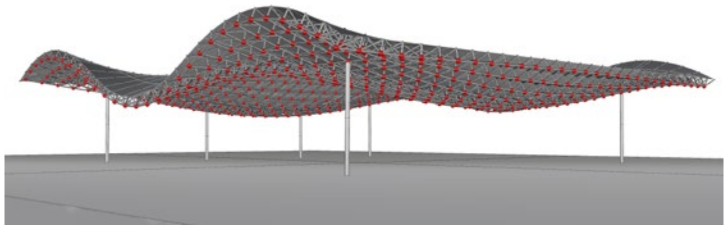
This design proposal is going to be used as a test case for the whole research and will help me prove the concept. All along there have been set some requirements that need to be fulfilled. Given that it is a double-layer free form structure, the span needs to be so large that the bending forces will require a double-layer structure. The proposed design is 60m x 60m and its depth is 1m. It is designed to for the needs of a train station, which also explain this span. The support points can be seen at the elevation view. Five representative points are selected (edge, corner, support, anticlastic and synclastic curve), in order to have an overall idea of the stresses for the specific structure at different locations. Emphasizing on the additive manufacturing of these 5 representative case nodes, will prove the manufacturing feasibility or not of all the other nodes.

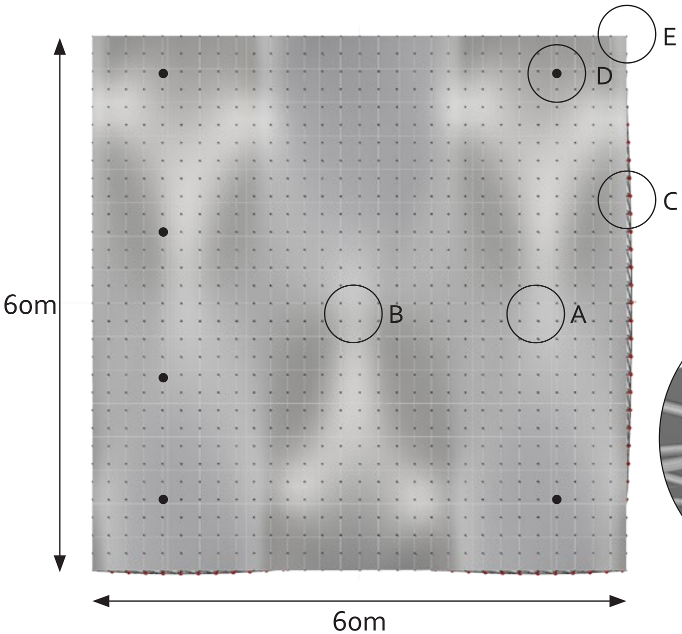
Process

The process followed for this design is parameter-based in order to make changing of curvature eay, so that once the algorithm is finalized to be able to run for many different designs. That is why its design is set up in a parametric environment.

Result



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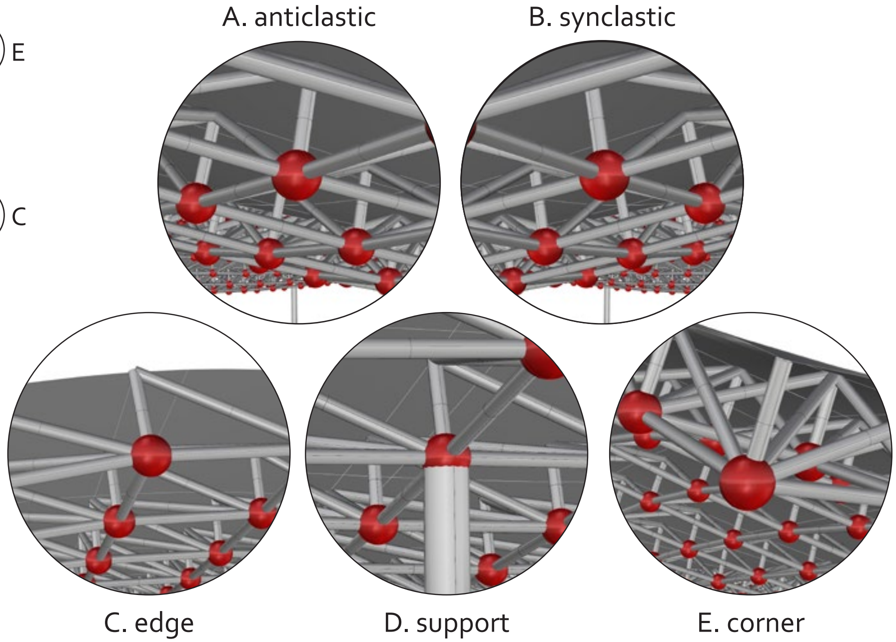
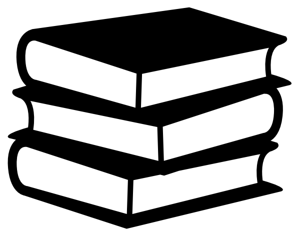

A. anticlastic
B. synclastic
C. edge
D. support
E. corner

Bibliography

- Chen, W.F., Lui, E.M. [2005] *Handbook of structural engineering*, New York: CRC Press
- Dunn, N. [2012] *Digital Fabrication in Architecture*, London: Laurence King
- Gerrits, J.M. [1996] The architectural impact of space frame systems, *Proceedings of Asia-Pacific Conference on Shell and Spatial Structures 1996*, Beijing: Civil Engineering Society
- Hopkinson, N., Hague, R.J.M., Dickens, P.M. [2006] *Rapid Manufacturing: An industrial revolution for the digital age*, Chichester: John Wiley & Sons
- IASS (International Association for Shell and Spatial Structures) Working Group on Spatial Steel Structures. 1984, Analysis, design and realization of space frames. *Bull. IASS* No. 84/85, XXV (1/2):1–114
- Iwamoto, L. [2009] *Digital Fabrications: Architectural and Material Techniques*, New York: Princeton Architectural Press
- Knebel, K., Sanchez-Alvarez, J., Zimmermann, S. [2001] *The structural making of the Eden Domes*, www.mero.de
- Kolarevic, B., Klinger, K. [eds] [2008] *Manufacturing Material Effects: Rethinking Design and Making in Architecture*, New York: Routledge
- Kotnik T. [2010] Digital Architecture Design as Exploration of Computable Functions, *International Journal of Architectural Computing*, 2010, Vol. 8, Issue 1; 1-16
- Lim S., Buswell R.A., Le T.T., Austin S.A., Gibb A.G.F., Thorpe T. [2012] Developments in construction-scale additive manufacturing processes, *Automation in Construction*, 2012, Vol. 21; 262-268
- Makowski, Z.S. [1981] *Analysis, Design and Construction of Double-Layer Grids*, Essex: Applied Science Publishers
- Motro, R. [2013] Nodes and Structures – A Tribute to Stephane Du Chateau, *Proceedings of the International Association for Shell and Spatial Structures 2013*, Wroclaw
- Rivas, S., Greig, A., Blackman, S., Tizani, W. [1999] Robotic Welding of Tubular Nodes, *Proceedings of the 16th International Association for Automation and Robotics in Construction*, Madrid, Spain, 1999;603-607
- Schodek, D., Bechthold, M., Griggs, K., Kao, K.M., Steinberg M. [2005] *Digital Design and Manufacturing: CAD/CAM applications in architecture and design*, New Jersey: Wiley
- Stephan, S., Sanchez Alvarez, J., Knebel, K. [2005] *Reticulated Structures on Free-Form Surfaces*, www.mero.de



[1] www.wikipedia.org
[2] www.experienceenglish.com
[3] Chen, Lui, 2005
[4] Gerrits, 1996
[5] Motro, 2013
[6] Chen, Lui, 2005
[7] www.wikipedia.com
[8-9] Knebel et al, 2001
[10-13] Stephan let al, 2005
[14] www.wikipedia.org

Schedule

Tasks				February																							
	Th	Fri	Sa	Su	Mo	Tu	We	Th	Fri	Sa	Su	Mo	Tu	We	Th	Fri	Sa	Su	Mo	Tu	We	Th	Fri	Sa	Su	Mo	Tu
	29	30	31	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
P2 presentation																											
Finite Element Analysis																											
Reject/Approve Fabrication Techniques (literature based)																											
Specimens Preparation																											
Specimens Fabrication																											
Specimens Testing																											
Specimens Data Sorting																											
Importing Data as a material database																											
Nodes Generative Algorithm Creation																											
P3 presentation																											
Finalize Node Generative Algorithm + Dimensioning [structural analysis in parallel]																											
P4 presentation																											
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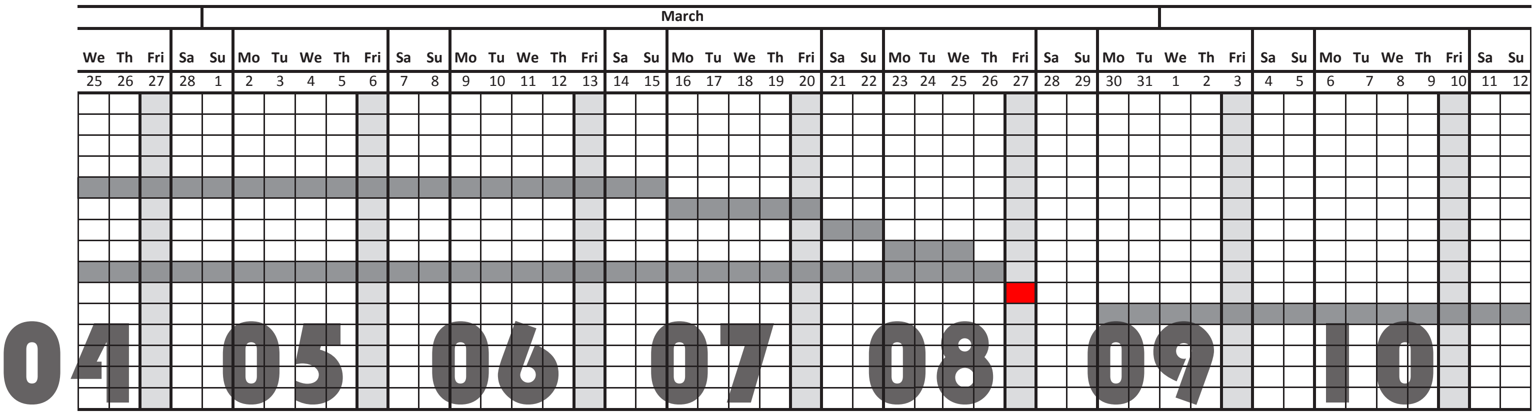
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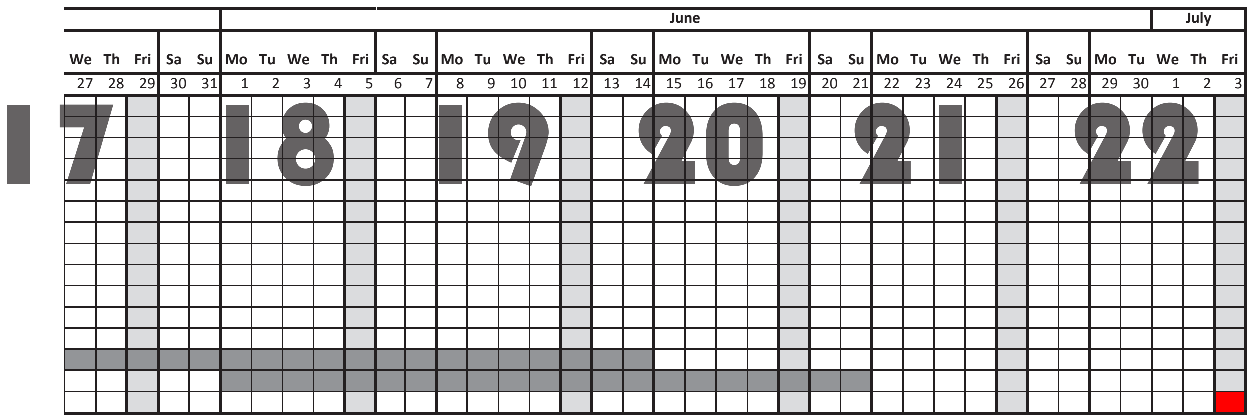
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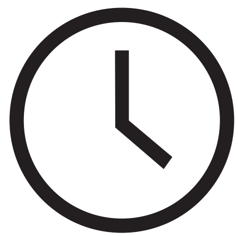

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