Towards Defining 'Process': a rereading of CAD methods within sculptural practice

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Grasshopper 3D community

Abstract

In what ways does Computer Aided Design (CAD) software and manufacture affect ‘material’ [1] and process in sculptural methods as evidenced in outcomes? For this paper the dual reading of materiality is taken. The word matter “came into English from the old French materie,” referring to “a building material usually timber” (Hong, 2003). Material however is not solely defined as being made of matter; it can be, for example, information used for writing a book. The latter terminology applies to digital artefacts substantially being information. Leonardi writes about “digital artefacts as having ‘material’ properties, aspects, or features, we might safely say that what makes them 'material' is that they provide capabilities that afford or constrain action.” He further proposes, “in the case of digital artefacts, what may matter most about 'materiality' is that artefacts and their consequences are created and shaped through interaction" (Leonardi, 2010). This research aims to investigate processes through utilising CAD and Computer Aided Manufacture (CAM) to inform specific historical sculptural methods based upon traditional sculptural processes (reductive, additive, fusion of material and reproduction) such as those of carving wood, modelling in clay, joining of metals, mould making and casting for reproducing form.

1 Material as in the matter of which a thing is made.

Introduction

Processes that stimulate creativity are part of material exploration through fabricating sculpture. Prior to this research, these explorations have resulted in artefacts broadly defined as abstract sculpture in organic materials. Utilising different materials and tools through comparison teaches specific qualities about each material, tool and technique. If we have an idea to create something, we may decide which material best suits that concept based on our knowledge of materials and processes to fabricate. Digital and CAM 3D forms are made evident through ubiquitous computing; the challenge is now, how can CAD and CAM systems reveal their inherent properties and specific materiality as characteristics that could similarly stimulate creativity? To define processes through these systems serves as a challenge, as previous cognition of process has been developed through a negotiation with material made of matter.

Organic materials retain the evidence of their origin; through working with them we may substantiate a connectedness to that environment. The material that technological hardware is made of is largely removed from its raw natural state – we witness this when it goes back into the environment as trash, taking decades to biodegrade. The science and engineering that run machines is referred to as artificial intelligence (AI) and the housing for these machines is mainly made of plastics; unnatural. To start, the investigation confronts material polarity; from the natural to the simulated through AI; operated by a human being through an artificial interface.

The research encompasses a shift from making work in a private studio to an interface-based collaborative laboratory, made possible through shared software, code and a platform hosted on the World Wide Web. Objectives here can become common and individuals' research may have significant impact on other people's investigations. In an attempt to conclude how this fast processing of information can be of service to a sculptural practice based on existing current knowledge, outcomes are discussed.

CAD

Parametric Modelling

The SolidWorks program has been developed with the intention of facilitating the design of objects through an interface that is compatible with CAM processes. Space on the flat screen is defined by Cartesian co-ordinates; views are referenced by planes and sets of functions are governed by dimensions. There's an absence of matter in the material depicting volume. Functions are based on points, lines and shapes such as squares, circles and rectangles. These functions start with infinite dimension best described with ‘0’, which has no beginning or end; therefore the first action is to add.

Functions are understood parallel to analogue methods of fabrication. In SolidWorks, a project begins with the drafting of a flat shape on a plane, then the boss extrude function is used to create a volume, termed a 'solid'. Executions like this are familiar in a ceramic studio; clay can be extruded through profile shapes. Clay allows for both subtractive and additive sculpting techniques without requiring an agent such as glue, the same is true for CAD – adding and subtracting volume is fluid to the inherent mass. Although there’s no sense of gravity,[2] objects can be rotated through the interface, navigated through planes and follow a method of logical construction processes like that of fabricating a building.

For the purpose of milling the form out of timber with a three-point axis CNC machine, a stepping pyramid consisting of extruded profiles is created (Figure 1). Variation in the form of further boss and cut extrusions being added to the front, back, left and right planes. The approach: an aesthetic random distribution, working around the pyramid structure until the generic stepped pyramid has enough variety to be interesting from different sides. The open-ended design serves the purpose of production, approaching the material from the top surface and then the bottom using the same model to create a form out of one block of wood.

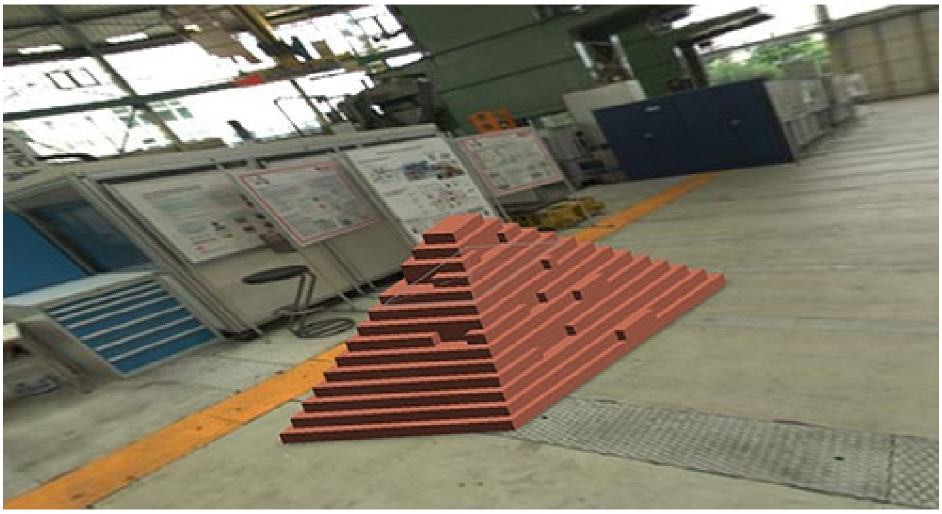


Figure 1: Stepped pyramid model created in SolidWorks.

In SolidWorks, the depiction of 3D space, volume within that space and the studio environment through an interface are artificial. There’s lack of differentiation between functions: whether joining two surfaces or creating a boss extrude, it all sounds like a series of mouse clicks and an occasional keyboard tap. If we are to join two surfaces in mild steel, through welding, we position the body, cover the eyes and have a good

2 Gravity is an animation physic feature applied to a finished model separate from the fundamental CAD design process.

second’s worth of concentration; adjusting our eyes and co-ordinating our hearing and body to make sure that connection is a perfect weld. There’s a residual smell and some of the metal will remain hot for a short period thereafter. The sensation of creating a weld, to join two surfaces, is absorbed through multiple senses in the body: SolidWorks doesn't smell; it requires a consistent posture of sitting at a desk; though there can be some hand and eye coordination involved depending on the task, generally operating functions are done effortlessly with a mouse, its operation is through the mind.

Sculpting out of a block of wood is commonly defined as a reductive process, taking out material to reveal form. When we start to understand material sculpturally we prescribe just the right amount of force to manipulate matter to a desired result. With the set of automated tasks performed through SolidWorks to create the stepped pyramid the only force used is the clicking of buttons and how fast or hard that’s executed is irrelevant to impact upon the material. If we are to mistakenly delete part of our model we can undo the procedure and revert to its prior state. The perception being that we’re sculpting with parameters and software limitations, with virtual space as our material.

In the realm of SolidWorks we can accurately build models to dimensions at fractions of a millimetre. To work with such precision lends itself well to engineering; we model on the foundation of planes with the fundamentals of geometry. From these models we can draft plans and elevations to have executed by industry or refer to when making in a workshop.

In CAD, how we allow process to influence our work is removed from ways in which we me may embark on reductively sculpting timber or stone using mallet and chisel. This is because organic substance is unpredictable, too hard, too wet, brittle or fractured. To craft in these media becomes a negotiation between the intent of the maker and the nature of the materials. A window of opportunity exists where material can influence processes while fabricating, evidenced in eventual outcomes.

The operation of utilising our hands in combination with tools on material is instructed by the mind. In CAD, variables are minimal; software is programmed to act specifically to instructions, after an action returning a Boolean value, true or false. Crafting material made of matter has more properties and variables, the response isn't just black or white; grey exists. The grey area can be perceived by the body through experience: our body learns to respond to material, immediately escaping the mind, prolonged absence of the mind can be described as flow. Flux and flow become instrumental to creating something other than preconceived by the mind.

Algorithmic modelling

Rhinoceros (Rhino) is a Non-Uniform Rational Basis Spline (NURBS) modelling program, generating mathematically defined curved surfaces or precise freeform surfaces. Rhino lends itself well to freeform modelling, though it's possible to create a solid. Unlike SolidWorks, when working in Rhino one is surface modelling. Grasshopper extends the capabilities of Rhino, operating through the same viewport but with a separate graphic user interface (GUI). Grasshopper is a visual programming language (VPL), virtual components are plugged in together to create results. The component can be a point, curve or surface, or a function such as a loft, possible in conjunction with curved objects. Values extend to complex formulas. Objects, functions and values are combined to generate scripts rendered through the Rhino interface, in Grasshopper 3D we're working with algorithms that generate outcomes.

Grasshopper is perhaps better described by its former name, Explicit History (Fano, 2008). The VPL allows us to see the whole algorithm generating the outcome and to intervene within any stage of that sequence. (In Rhino, this sequence would need to be undone, or staged with multiple saves to refer back to.) This allows us to take an algorithm and combine it with a multitude of components. The Grasshopper VPL is dynamic, in contrast to the agency of applying force to material, exemplified by the act of reductively sculpting, where the moment of mallet hitting chisel, impacting stone, is lost in time. Grasshopper allows us to develop and explore multiple time lines, preserving prior executions. Reverting to an earlier copy or splicing two or more sections of code is all made possible with the linear componentry display.

Once an algorithm is created it's possible to share and release it on the internet with a general public license (GPL). The Grasshopper website is a platform where users can share these creations and techniques, it’s also a repository to pose queries to avid developers. Viewing the stream of image uploads serves as inspiration; a broad variety of users from different professions are working with Grasshopper. Seeing people’s deployment of the software, also in combination with other technologies, opens up new creative possibilities: integrating physics or external data and devices, ranging from sound, map cartographies, mobile phones and sensory adaptors. It’s a collective ethos where people share their knowledge, creating a rapid growth in users adding back into the community’s expansive cloud. "The idea of the artist as social recluse or a cultural lamplighter of genius is an inadequate representation in this day and age" (Sullivan, 2005, p.151). The collective dynamic of the Grasshopper community is a hive, where ideas cross-pollinate globally between, artists, designers, architects and further afield.[3] Through sharing resources, individual authorship is nullified; developing upon other people’s frameworks, the creation of mechanisms

3 Indeed I am indebted to the Grasshopper community for support in realising this project.

occurs that embody the rhizomatic nature of the World Wide Web.

Sharing knowledge freely means that other individuals rapidly acquire skills; these people can be seen as users. A natural phenomenon is that some users will remain users and others become contributors. Through the Grasshopper platform these people discover, invent and share new code snippets or screenshots and videos of their results. This is beneficial because others may see ways to improve or give feedback on that code snippet or media. It's a ripple effect; users will possibly adopt the code and if they share their adapted deployment of it, the community gains. Although this research starts from a user's perspective it is my intention that I too will discover or invent new code snippets or outcomes that may be beneficial to the community. It's likely others will give feedback, possibly develop or improve upon my findings, extending the research.

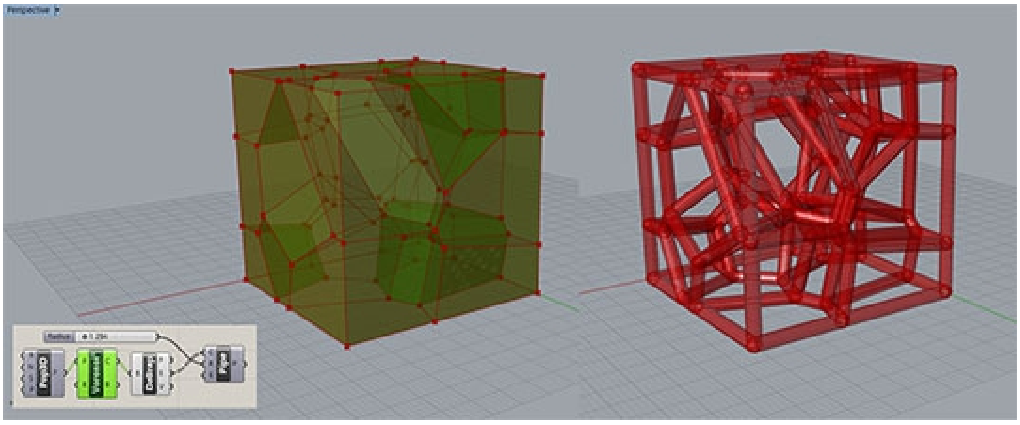


Figure 2: Voronoi 3D in Grasshopper developed version from the Studio Air video tutorials.

Through Grasshopper we quickly arrive at creating a 3D form by combining a number of components (Figure 2). Beginning with a box, 'Voronoi 3D' divides the space within the box into a number of regions; these areas are defined by a set of points placed within the parameter of the box, the areas created around these points are known as Voronoi cells. It is necessary, for 3D printing, to give the model thickness; a simple solution for a wire-framed object is to use the 'pipe' function.[4]

Ian Stewart (1995) writes, "the simplest mathematical objects are numbers, and the simplest of nature's patterns are numerical" (pp.3-4). Furthermore, he explains mathematical objects to be "idealized models of certain features of the real world; they are not real things, and they do not correspond exactly to real things" (Clarke & Mandelbrot & Stewart, 2010, p.4). Models such as these are found in the sciences; Grasshopper output has a scientific appearance that may illustrate aspects of the actual world. Galileo referred to the universe as "written in the language of mathematics" (Stillman, 1957); to understand the universe required

4 The cap function within the pipe component can be utilised for closing the open ends of the pipes.

an understanding of mathematics. Artists have been interpreting the natural world for hundreds of years (Sullivan, 2005, p.14). We can imitate biological form by casting from an original object, use 3D scanning technology or sculpt in a medium that allows us to deviate from the original, abstract it or infuse it with expression. Replicating biology by reverse engineering using mathematics can be accomplished by reducing form in terms of geometry and patterns; these patterns and geometries are further reducible by numbers. Using Grasshopper we can apply this data to devise an algorithm, arriving at an idealised model of the subject.

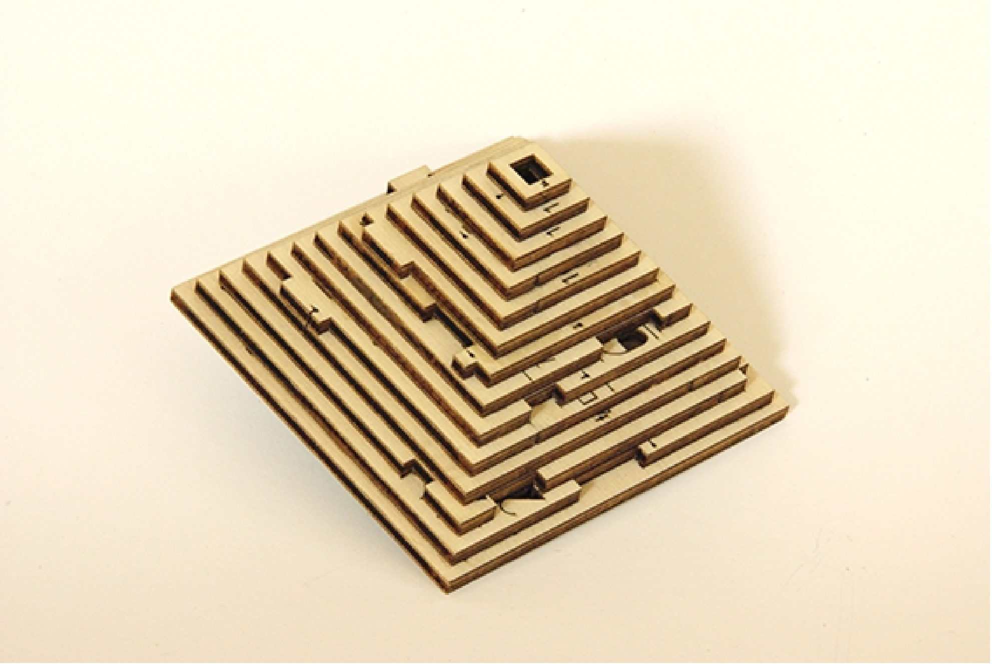
In a departure from its representational function, Grasshopper can be used to create bespoke algorithms through the language of the universe (mathematics) and can serve to output unique forms. These new entities become less a question of interpreting the world and more about mathematical structures speaking directly. Philosopher Pierre Levy refers to this creation of a mechanism as to "enable the silent component of cosmic creativity to give voice to its own song" (1998, pp.184-5). These mechanisms can be perceived as ingenious due to the extraordinary intellectual and creative powers inherited from the multitude of authors.

Agency

Reductive and Additive Sculpting

The formal simplicity of the stepped pyramid model created previously in SolidWorks was necessary to enable the computer numerical control (CNC) milling machine operating from a one-point axis to excavate the 3D model. The stock for this project is Matai, a timber native to New Zealand. It is of medium density, desirable for detailed carving. The process is executed in two phases: the outside is milled; when complete the stock is turned upside down and placed with precision; the inside is then milled to complete the model.

In order to compare, another method was deployed to execute the model (Figure 3): creating file paths for the digital laser cutter using a software known as 123D Make that slices the object into the thickness of the plywood stock. After laser cutting, the ply parts are glued together to complete the 3D form. The laser cutter leaves scorch marks on the edges, contrasting the horizontal and vertical faces. This emphasises the components that make up the whole. The method of fabrication and construction is evident in the object's final appearance.



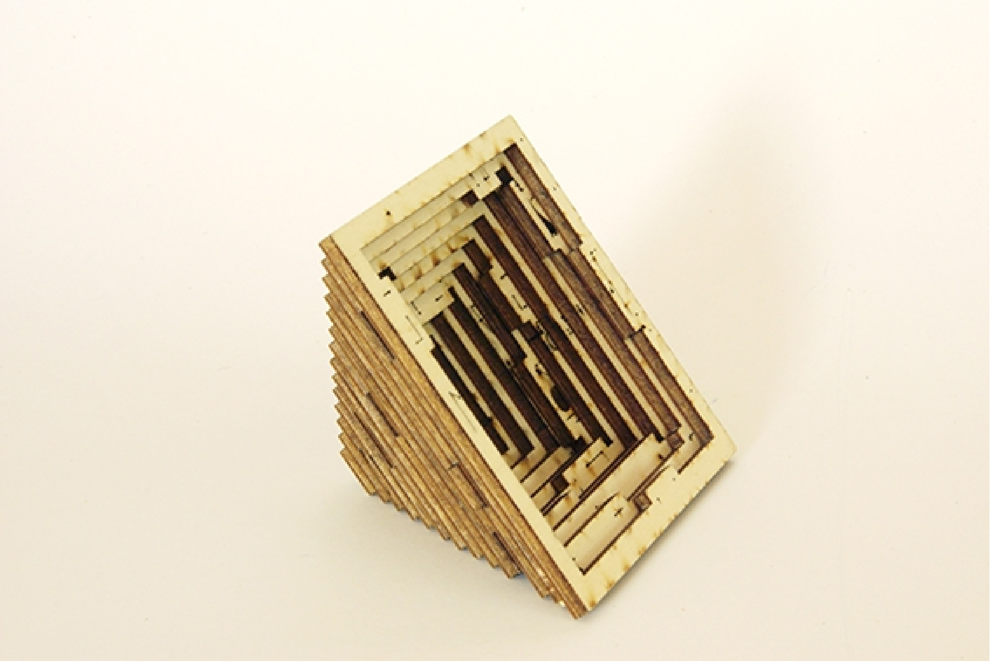


Figure 3: Stepped pyramid, laser cut assembly, 90 x 90 x 56mm.

Figure 4: Stepped pyramid, CNC milled timber, 110 x 110 x 41mm.

In contrast, the CNC model varied from the original model. On the internal corners, rounding had occurred due to the curved tip on the drill bit. This softened the straight lines, smoothing the steps (Figure 4). The grain of the timber is visible throughout the whole object, its fluid structure in contrast to the stepped geometry. Not exactly evident is how the object has been manufactured. Its form suggests a stepped growth pattern but on closer observation it actually looks like a reductive process. The precise execution does suggest CNC milling has been used as a tool to reductively sculpt this form – arguably it could also have been made by a detailed craftsperson.

The cracked edge from the millimetre excess in stock gave a new characteristic to the work. The contrast to the straight lines differentiates this edge and emphasises the fragility of the modelled material. Although the artefact is a singular unit, the stepped structure is made of many components that form a continuing pattern. The cracked edge also suggests the possibility that it was a part of something else. The incompleteness raises questions and opens up the imagination: we try to solve, complete and gain new understanding (Sullivan, 2005, p.115).

When we read form, the material it's made up of is inherently a part of that interpretation: size, weight, density are all factors. Furthermore we reflect upon the environment it's located in and which fabrication process it may have undergone. The method of back-formation to carve stone or timber is a traditional approach to fabricating sculpture. A mass of organic material such as stone or timber has integrity, it has undergone a process that takes time; with timber, decades of endurance. The material is dense and the structure organic, therefore unpredictable. It's not malleable with just hands, the fabrication is with tools that become an "extension of the body; it is the virtualisation of an action" (Levy, 1998, p.95). There's skill and sensitivity required to respond to the material through our tooling. While sculpting we tend to move around the material; creating cavities within this mass has limitation as we need space for our tools and our hands need to be operable, not all forms are possible and we marvel when these limitations are pushed.

When reductively sculpting abstract works, the outset can allow for process where the outcome is varied from the initial intent. This variable is often a response to the material's properties and the tools used to deduct material. It is an archaeological excavation, there are clues of what lies beneath the surface but the result of what is discovered can be surprising. We know the risk that if the material is worked too forcefully or hastily we may loose an opportunity or end up with an undesired effect. Removing the bulk of the material and arriving at the surface of the form, we have sensitivity to the remaining deduction of material, knowing that where too much is removed we cannot simply add back on (Panek, 1999, p.39).

The CNC machine is blinded to this process, the artefact is superimposed inside the area of the material and the machine goes to work to excavate around those parameters. It does not deviate from the given path nor does it respond to the direction of the grain if the timber starts to splinter rather than cut; it has no tacit knowledge or awareness of itself.

During manual fabrication an immersion takes place into the material, technique and ideas surrounding a work. A deepening of understanding, this comprehension of the moment is not to be confused with our brain analysing and deciding upon what action to take. Experience has been acquired through our body, tools, the materials and how they respond. Yes, we can analyse and make decisions through our intellect, but our body is responsive in the moment of making, it feels and is sensitive to, often on automatic pilot.

The sense of connectedness to the material through the tools at hand is removed with virtualisation of CAM. We are bystander, spectator and left out of the game. The opportunity for development through the process of making is different; our tacit knowledge is exercised through the filter of the mind. The new parameters raise the question how do we push CAD or CAM beyond automating tasks and develop new strategies that allow process to influence sculpted outcomes (McCullough, 1998, p.68)?

Fusion Sculpting and Reproduction

The Voronoi 3D cells model was printed with an UP 3D printer (Figure 5). The printer creates a framework from the same Poly Lactic Acid (PLA) plastic material within the negative space of the model to support the printed part. Noticeably, after the 3D printer finishes, the result is an apparently solid cuboid compromise of form and support material. With great care, a craft knife can be used to extract the printed support material from within the 3D printed model. This tidying up is not removed from other kinds of production related to artefacts. When forming metal through lost wax casting we're left with sprues; traditionally these are cut from the cast, ground back and fettled to conceal the casting process.

It is possible to frame fused deposition modelling (FDM) as a casting process. The filling of negative space with a support framework serves the flow of material in a similar fashion to that of the investment mould used to parametrise the flow of metal when cast. In FDM, the material's temperature is set at a rate that's hot enough to be extruded through the machine's tip; this means a temporary support structure can be created to support printed parts travelling into space, while the temperature of the material remains hot and is pulled down by gravity. The fineness of the tip's printer head means the support can be connected at points with very little thickness; this enables the support to easily break away. The material has flow, and a path it follows in the given space occupying the digital model serving as a boundary, similar to that of an investment mould for bronze casting.

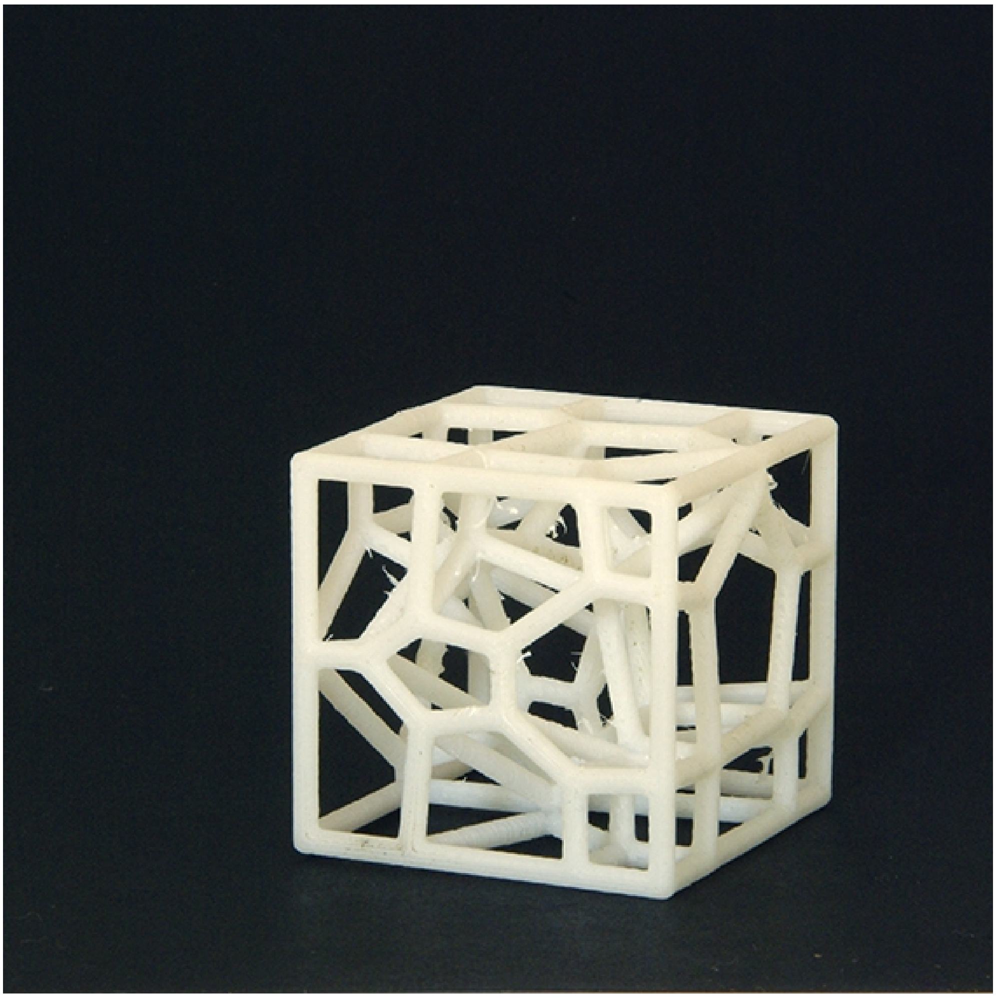


Figure 5: *Voronoi cells 3D*, 3D printed in PLA, 42 x 42 x 42mm.

Figure 6: Bronze casting at foundry de Kameleon, Haarlem, The Netherlands, 2004.

In casting bronze, the process is very rapid as the metal is quick to cool once it's poured (Figure 6). Care is taken to generate enough sprues so the material can be evenly distributed. As the metal is poured into the mould it resurfaces through vents, showing that no air pockets are formed that might result in an absence of material in the form. This is because gravity pulls the liquid metal down and it rises up for the duration of the pour. The support is a mould made of a plaster compound that can be chipped off once the metal has cooled. In FDM the role of the support created in synchronisation with the model differs to that of the ceramic shell mould used in the casting of bronze created prior to the pouring of metal into it. It is the digital model that dictates the boundary of the form, not the support material. In aid of reproductive function traditional moulds and CAD models share commonalities, unique to FDM is the computer controlled temperature, timing and location at which the material is deposited. This technique of fusing material to reproduce form is particular to 3D printing.

One of the beauties of CAD modelling software is the ability to rapidly create a mould from a model. For two-piece moulding it's a matter of superimposing the model on two containers and deducting the overlapping model from the container, this now being your mould. The same rules apply when analogue mould making, the form must lend itself to be released from two containers, burying no underside. Mould making outside of CAD is a labour intensive, time consuming process – a typical two-piece cast consists of the form to be moulded in a container to carry the plaster poured as liquid (Figure 7). Depending on plaster grades and ratios to water, the result allows inconsistencies from tiny air bubbles in the plaster. These bubbles can be left or repaired, adding to the manual labour involved. A quick, by comparison, multiple-step process of clicks in CAD results in a mould with no extra cavities generated by bubbles of air: when we create a digital model the opportunity for reproductive errors is removed.

Figure 7: Mould fabrication process.

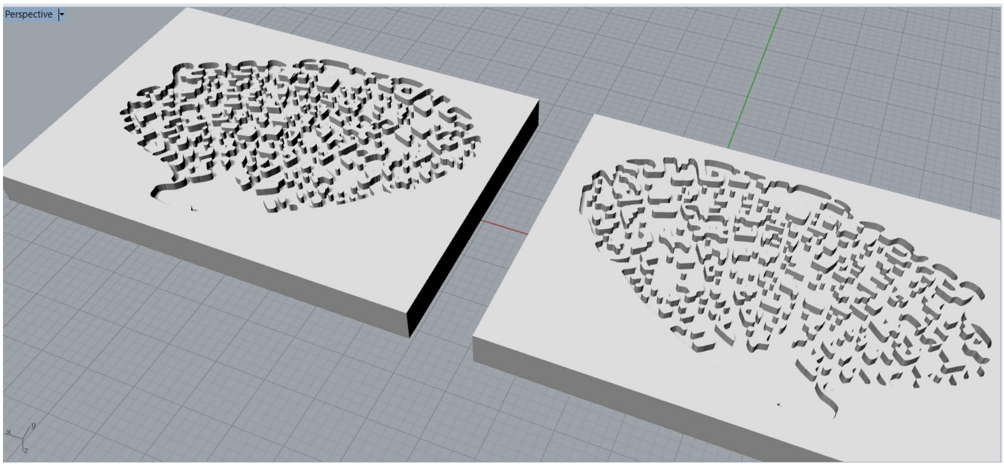


Figure 8: Digital mould in Rhino.

A further connection between casting and CAD is illustrated by the EOS 3D printer machine’s manufacture of the model by fusing particles. The printer’s stock is a box of nylon particles; the volume of this box is loaded, through an interface, with digital 3D models. The positioning of objects within the boxed area is similar to that of loading a kiln when firing ceramics. Ceramics are already formed before they enter the kiln but, like the EOS 3D printer’s process, the particles fuse with the rise in temperature.

The PLA plastic printer builds a support around the printed object; the EOS 3D printer already has the nylon particles as a support. Some clay objects while being fired risk slumping if they’re insufficiently supported, it’s not uncommon to fire a ceramic form together with ceramic supports. The processes share commonalities; the way in which the matter is fused differentiates the two. The firing of ceramic is a cycle where the kiln is brought to a desired temperature gradually then held at that point of maximum, while the entire clay particles sinter and fuse together as the temperature is slowly decreased.

The fusion of nylon particles by Select Laser Sintering (SLS), executed through Cartesian co-ordinates, dictates a linear path from bottom to top. The laser fuses the particles where the digital model is located in sequence, after all the models have undergone laser sintering, the objects are excavated by removing the remaining nylon particles. The 3D printed models can have a less than 1mm wall thickness, thinner than the finest porcelain possibly produced through ceramic firing. The 3D printed material is of lighter weight and has flexibility combined with its strength. For ceramics, although the material has strength, it’s rigid and prone to breakage.

While nylon can be dyed, it can't be glazed as it has a melting point of 180 degrees centigrade. Its low melting point means 3D printed nylon or PLA plastic models can be substituted for wax models in the lost wax process for casting metals: this technique has coined the name, lost PLA casting. The Z-Corp 3D printer builds models in gypsum-like powder; the fusion of particles is with a liquid rather than an SLS process. The nature of these models is very fragile, though they can be strengthened with resin. An advantage to printing in this medium is that the models can be glazed through a kiln firing.

Scale

Assemblies

The scale of 3D printing is commonly defined by a print envelope of approximately 300 x 400 x 300mm. There are large-scale custom-built printers for creating projects such as a 3D printed house (Vermeulen & de Wit & Heinsman, 2013). However, even in a project of this scale, it consists of assembled components.

Through the Rhino GUI we have a sense of proportion but not scale in terms of physical space; when we initiate prototyping the form, we're advised to set the environment in terms of millimetres, centimetres or metres – more fascinating is the option to model in nano-meters. High precision 3D printing has been realised using liquid resin set with laser technology (Aigner, 2012). The vast scope in dimension is evidenced in this and comparatively for architects, who commonly use CAD, this scale range makes for flexible application.

Figure 9: *Te Tuhirangi Contour* by Richard Serra at Gibbs Farm, 252m x 6m x 50mm.

On visiting Gibbs Farm, a collection of sculptures of mega proportion on the Kaipara Coast, it is evident on closer observation the sculptures are assembled fabrications. To name an example, *Te Tuhirangi Contour,* by Richard Serra, at distance is perceived as a wall travelling through the landscape, for 252 meters to be exact. It is however an assembly of 56 6-metre tall by 50mm thick Corten steel plates. The plates were manufactured by a German steel mill, the transportation of the plates meant the wall needed to be comprised of components. Other factors serve an assembled makeup, such as the installation of the plates on the site. The nature of metal is to expand and contract depending on the climate, therefore 10-20mm of space is left between the plates; the plates are installed in such a way to allow them to move slightly when expanded in the heat. It's common sense to fabricate sculpture as an assembly when the scale exceeds the chosen materials' dimensions, and also for logistical purposes, such as transportation and health and safety for the general public. Projects of this scale by sculptors involve architects and engineers aided by CAD software.

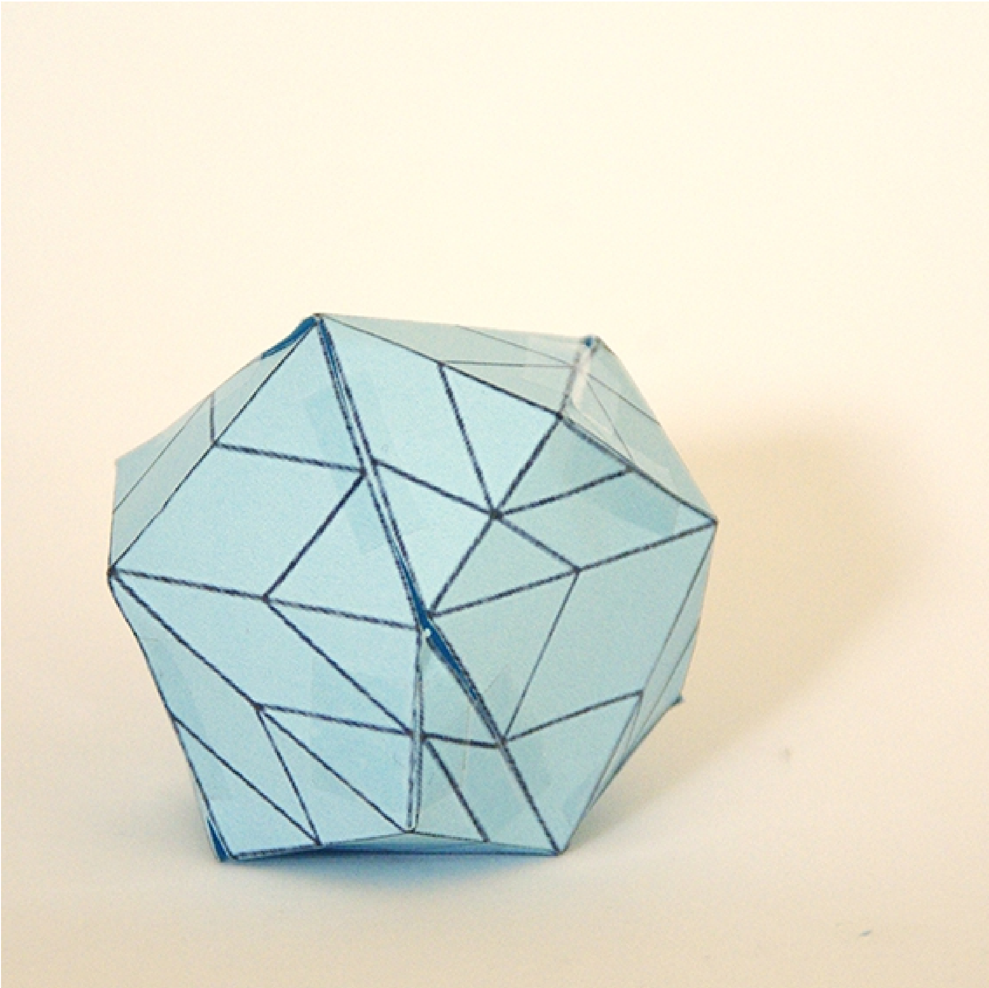


Figure 10: Planar paper model, 58 x 58 x 58mm.

One function we can use in CAD software is to unroll a surface. In the example above, the surface is unrolled from a faceted form generated by random points. Unrolling a surface can be applied to any form comprised of planar, as opposed to curved, surfaces. This illustrates how the surface unroll functionality in CAD is modular and can perform a fabrication plan for many forms.

The first unrolled surface consisted of a uni-surface and the second of separate numbered surfaces with flaps to join the fabrication (see Appendices A & B). The plan printed on paper included a CAD generated number system, which proved to have no logical order in terms of visual cognition; while some neighbouring surfaces did correlate in number sequence, too many didn't. The assembly process was heavily weighted on recognising the shapes and form of the first assembly (Figure 10). This type of abstraction is common using computational algorithms with the intent to manufacture; realising that complexity in form will lead to more parts, numbering of parts correlating to numbered plans of the model are necessary for assembling in this way.

Figure 11: Aluminium sheet metal assembly from surface unroll in Rhino.

In the second assembly a decision was made to use aluminium sheet metal; it's strong, thin and lightweight (Figure 11). The material being malleable with scissors, the riveting process isn't well suited to joining the panels; the combination of drilling holes and pressing rivets tears the aluminium, creating a weak bond; using glues as a binding agent or using stronger sheet metal may be more appropriate. The flaps standing almost perpendicular to the planes add strength to the structure, acting as an exoskeleton. It's possible to build a large self-supporting structure with this method of assembly, considering the material is strong and lightweight. Alternatively, metal plates can replace the aluminium sheeting for the purpose of strength and bonds can be realised through welds or further assembled components.

The fabrication process of cutting and assembling parts is a repetitive task, though the maker could decide whether to complete the assembly or leave it at a certain stage. The modular fabrication does carry with it a mandate; there are parts and they fit together a particular way. One does not readily evolve the model into something unforeseen because the variables of what's possible are reduced. Through task-oriented fabrication we arrive at the predetermined result; in this sense as makers we're adhering to a set of instructions, similar to CAM where a computer serves instructions for operating mechanisms to arrive at a set goal.

Proposal Writing

Creating large sculpture often necessitates securing funding, for which proposal writing is obligatory. Proposals typically include sketches or models to help convey the idea of the proposed work. Unless the work has been made prior it is often difficult to deviate from this. A proposal submitted for NZ Sculpture Onshore 2012 included a mock-up image of a perforated dish accompanied by an interactive augmented reality component (see Appendix C). The proposal being accepted prior to the work having been made meant the fabrication process worked towards a predetermined outcome illustrated by the mock-up. Fabrication of the perforated dish proved to be an exercise in welding and plasma cutting, a relatively task-oriented exercise that could also have been executed by a metal technician. The size and location of the dish demanded the installation ensure public safety; the supports created for this purpose were exposed and became visually distracting, which compromised the work to a certain extent. Engineering is part and parcel of large sculpture; unobtrusive support to the artefact can prove to be challenging.

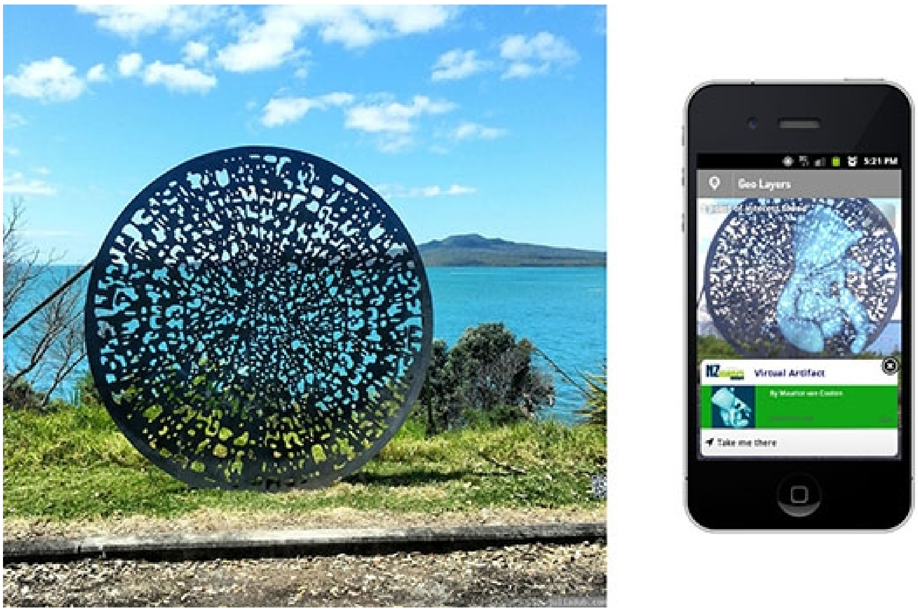


Figure 12: Left: *Deep Dish*. Galvanised steel, 2400 x 2400 x 150mm. Right: Virtual artefact, screenshot.

The augmented reality aspect gave the work a performative twist: accessed through their mobile phones, the audience viewed the virtual model geo-located on site (Figure 12). The application (App) deployed to view the virtual artefact does have user experience obstacles. Some people weren't able to access the artefact, others who were able bring the 3D model up on their mobile device shared this with people around them. This surprising element blurred the boundary of artefact and viewer, because an interaction took place that incorporated the public with the work, people became instruments to unveil this other layer to the installation. Previous sculpting work had located the unforeseen in the execution of the work, material having effect on the process, influencing form. The means of fabrication of the proposed sculpture left little room for development, but opportunity for discovery that was removed from the process of making found a new location: the live art event.

Symposia

In 2013 I was invited to participate at Wood Sculpture Live, a biannual sculpture symposium held at the Lake House Arts Centre in Takapuna. Wood lends itself particularly well to the possibility of emergence taking place during the process of creating work. Bowen describes emergence through thinking in a medium, "Frequently I'll screw wood just flat to the wall and look for some kind of form that may in some sense already exist there and try ... pull something out of it" (Sullivan, 2001, p.4). Something: that which is not known prior to undertaking. In studio-based work I've incorporated this process, yet found that while some forms are realised in days, other work demands further contemplation, leaving several months before completion.

Affordance of time is a restraint at sculpture symposia; to allow for emergence in the process of fabricating an unforeseen form does carry risk of not finishing by the end of the symposium or compromise to the artefact. Having a clear idea or model allows for calculation of tasks and a division of those tasks over symposium days; given that the preconceived idea isn't too ambitious for the time provided it's quite possible to finish on time or even early.

To frame this task-driven approach, CAM operates through a 'command line' of instructions initially programmed by people. In this sense, even if they are our own instructed tasks, sculptors can operate in a similar fashion if those instructions are unresponsive to affording allowances to deviate from the predestined model. For the sculpture symposium I decided to embody the 'command line' while fabricating, working from a preconceived sketch based on the stepped pyramid model crafted in SolidWorks.

Figure 13: *Emerging Cities.* Norfolk pine timber sculpture, 860 x 760 x 4600mm.

This work, *Emerging Cities,* consists of five stepped pyramids travelling upward in a zigzag fashion (Figure 13). The method of execution is formulaic: remove triangular sections down the front and back sides of the trunk, reductively pattern pyramids with steps, break pattern of steps with evenly distributed deduction of stepped sections. The execution, namely, a person moving around the log carving it with a chainsaw, made for allowances in precision. The procedure of deduction directed by commands being evidenced in what remains: the threshold of the medium has too negotiated the outcome with the executioner and chainsaw. The repetitive stepped pattern, from a carving perspective, is a repeating of a 'command line' over and over again. Removing timber to the 'command line' becomes like a Mantra, this Mantra can best be described as facilitating flow. With flow comes flux, a measure. Flux is evidenced in the cut traces of the chainsaw that remain, for while we're in the flow it's essential we cut deep enough to remove the section of timber, but not too deep that we create deep chainsaw cuts. Traces of this threshold of cut lines made by the chainsaw remain; honesty in tools that created the work. Textures from tooling too are discovered during sculpting; it's the decision to incorporate or hide these that's dictated by whether those marks add value to the work.

On observation, the shift from form-finding, provided by the affordance of process through fabricating in media that complement this approach, to making work in media that's less suited, or circumstance that hinders this process, has revealed a new property, namely pattern. There are many types and forms of emergence but it can broadly be defined as being a paradox: "changeless and changing, constant and fluctuating, persistent and shifting, inevitable and unpredictable" (Fromm, n.d.). In terms of a persistent pattern, emergence would be indicated by a changing component within that pattern.

The threshold of inconsistency within the pattern of *Emerging Cities* is also perceived in the differentiation of stepping; in the CAD stepped pyramid model the stepped sections were precisely 3mm vertically and horizontally across; carving with a chainsaw created thicker and thinner stepped sections in both directions. Together with the chainsaw cuts these elements, although part of the pattern, also deviate from it. According to Fromm this exhibits emergent properties. It is the larger or smaller, inflated or deflated, stepped sections of pyramid that suggest a changing pattern.

Process

Glitch

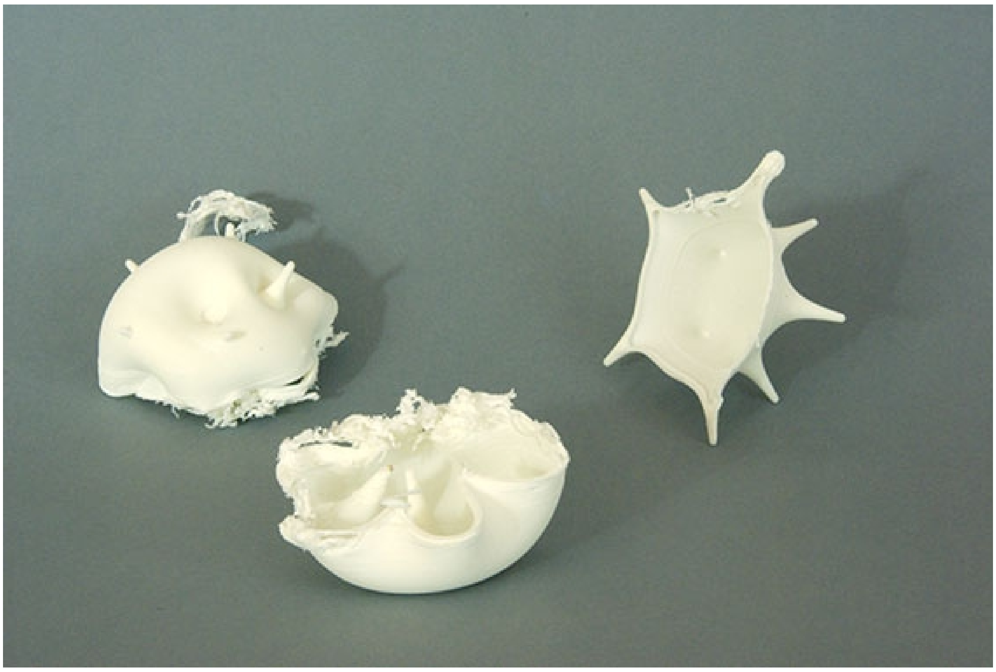


Figure 14: *Spatial Deform.* 3D printing glitch in High Performance Composite. 110 x 85 x 45mm, 65 x 75 x 40mm, 80 x 33 x 90mm

The above image shows the result of a 3D printer error generated when the printer stopped working and printed half the models, leaving plastic residues not part of the original design (Figure 14). It also exposed the internal cavity of the work. This happening came as a surprise. A common presumption is that this technology achieves a perfect and predictable result. It's not uncommon when crafting work in traditional sculpture materials such as wood, clay, stone and metal that processes don't turn out as initially desired. When a mistake occurs we are left to decide whether it is of benefit or to the detriment to the work, if it's the latter we may adapt and transform it, alternatively start anew.

Modernism and the Japanese aesthetic Wabi-Sabi "are abstract, nonrepresentational ideals of beauty" (Koren, 1994, p.25). Although both have similarities, Wabi-Sabi is often described as an antithesis to Modernism. Where characteristics of Wabi-Sabi are that its surface is earthy, imperfect, and variegated, those of Modernism are seamless, polished, and smooth. The printed 3D forms remain incomplete and imperfect; both are characteristics of Wabi-Sabi. Admittedly these works contain both Wabi-Sabi and Modernist aesthetic but are not exemplary of either one in particular.

Although initially by surprise we're confronted with imperfections, these are accepted by the artist and through the process integrated into the final outcome. The initial error or glitch becomes a desired and controlled feature. We may develop a practice that allows for the fundamental uncontrollability of nature, we may even purposefully create accidents.

The book *Glitch* (Moradi, Scott, Gilmore, & Murphy, 2009) is a compilation of computer glitches taken as screenshots. The phenomenon is created when there is a glitch in the system; when that is momentary it becomes quite transient and it is difficult to define the cause. In the 1990s as part of the electronic music movement artists developed sounds with glitch material, such as CDs skipping and further digital or electronic distortion (Cascone, 2000).

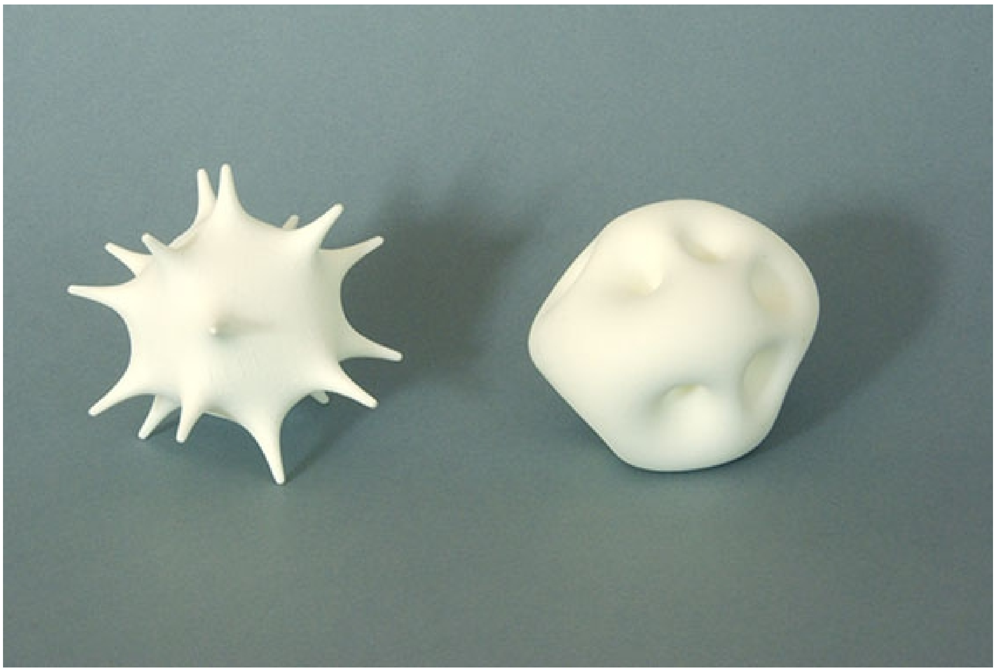


Figure 15: *Spatial Deform*. 3D printed in High Performance Composite. 80 x 80 x 90mm, 85 x 65 x 75mm

Noticeable after 3D printing *Spatial Deform* the second time, into the world of gravity they now stood like a jellyfish washed ashore (Figure 15). Estranged from their natural environment something of their world was lost. Their scale was stolen, what appeared to have possibly been micro or macroscopic was neither, but small enough for a display cabinet. Before, they were intrinsically connected to a larger network defined by x, y, and z and other bounding points, lines or geometries with added tensions or relaxations, now their connections had been cut and were left to roll and be placed about in our world, frozen in plastic.

Chance

Chaoscope is a computer program designed to help comprehend dynamic systems. Mathematicians describe how this works in terms of chaos theory. Through the Chaoscope function 'plasma', a form can be generated with dynamic system data. Saving the model with a file extension recognised by Rhino means it can be imported for further adaptation. The model consists of points and curves; using these as references Grasshopper can add thickness to the curves, or objects such as spheres to the points (see Appendix D). The latter resulted in numerous spheres contained within a cuboid parameter. Manipulating the dynamic system data model resulted in a mass of spheres that resembled a bubble structure, looking similar to the structure of polystyrene; this can be sculpted reductively to manipulate form, leaving a texture of neighbouring bubbles. Removing multiple spheres around the cuboid resulted in a variation of the formation as shown in the image below.

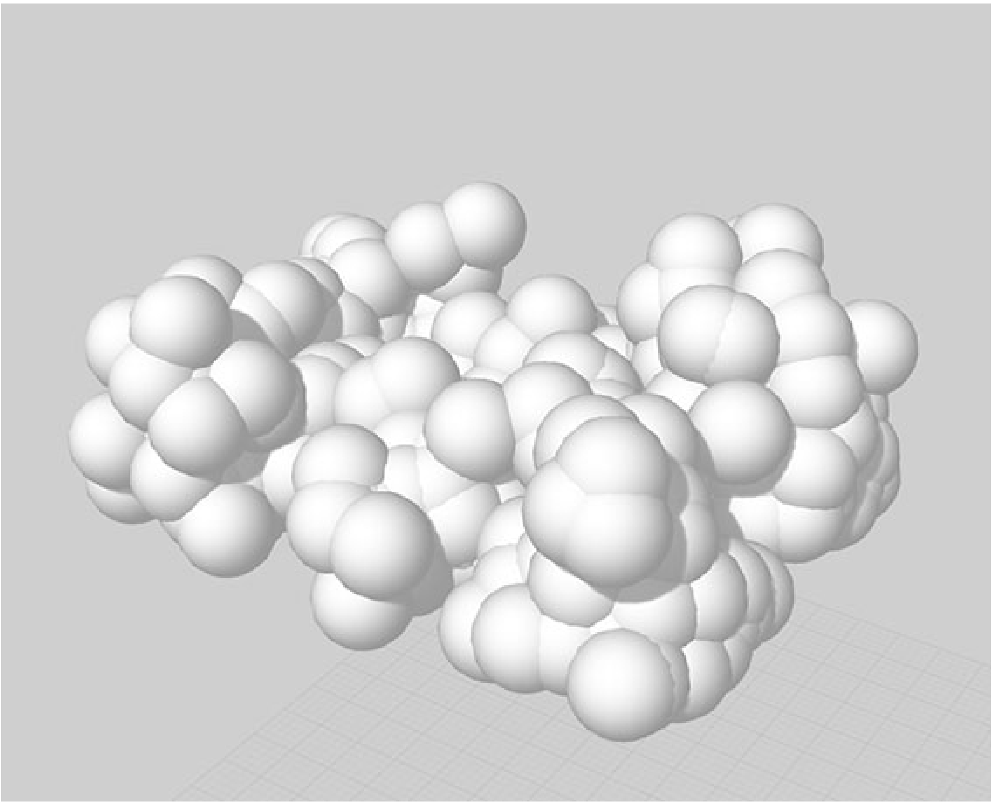


Figure 16: Dynamic data system model.

To learn software we can follow tutorials and use the package in its proposed way; through direct use of the software it's possible to arrive at unconventional results. Before the software’s functions are understood we navigate the unknown. The process allows for chance to occur because we're not directing a linear path to arrive at an outcome we think to achieve, the potential here is to build upon these initial findings when we perceive them to be of qualitative value.

Another way to work with data is to input an image through Grasshopper, which interprets darkness and light on images; these can then be assigned outputs (see Appendix E). Different types of data can be utilised, alternatively manipulating one data set in as many different ways leads to discovering the software's functions and generates new forms. On reflection of these first attempts at discovering form through CAD, the manipulated dynamic system data generated by 'plasma' in the Chaoscope is sculpturally significant (Figure 16). The form produced differentiation dependent on which way the model is observed, and invites the viewer to perceive it from varying viewpoints. The repetition in spheres produced a pattern, chaotically positioned, contained within an oblong parameter. Through the paradox of order in the repetition and chaotic placement within a parameter, a form is revealed that has emergent properties, appearing organic.

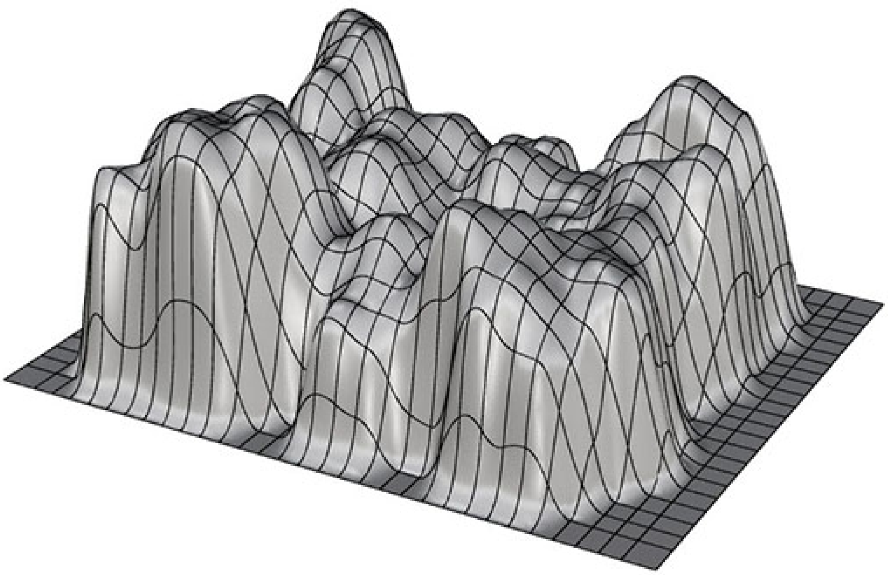


Figure 17: Dynamic data system draped model.

The bubbled structure suggested a material quality, although it being a CAD model this material is virtual. Using functions in Rhino, such as 'drape', a simulation is created of a surface that's pulled over an existing object (Figure 17).[5] The process is similar to that of vacuum forming, where a sheet of plastic is moulded with heat and suction over a physical object. Through draping over the dynamic system model, the remaining form now resembled a section of a 3D modelled cartographic map. The function being one dimensional, linear travelling over the object results in smoothing, no undersides of the sphere remain evident in the model. CAD can manipulate form through utilising functions in combination with another form; the

5 The threshold of accuracy can be adjusted when using this function.

consequence of these actions simulates affordance that denotes these objects inhibit virtual space defined by Cartesian co-ordinates.

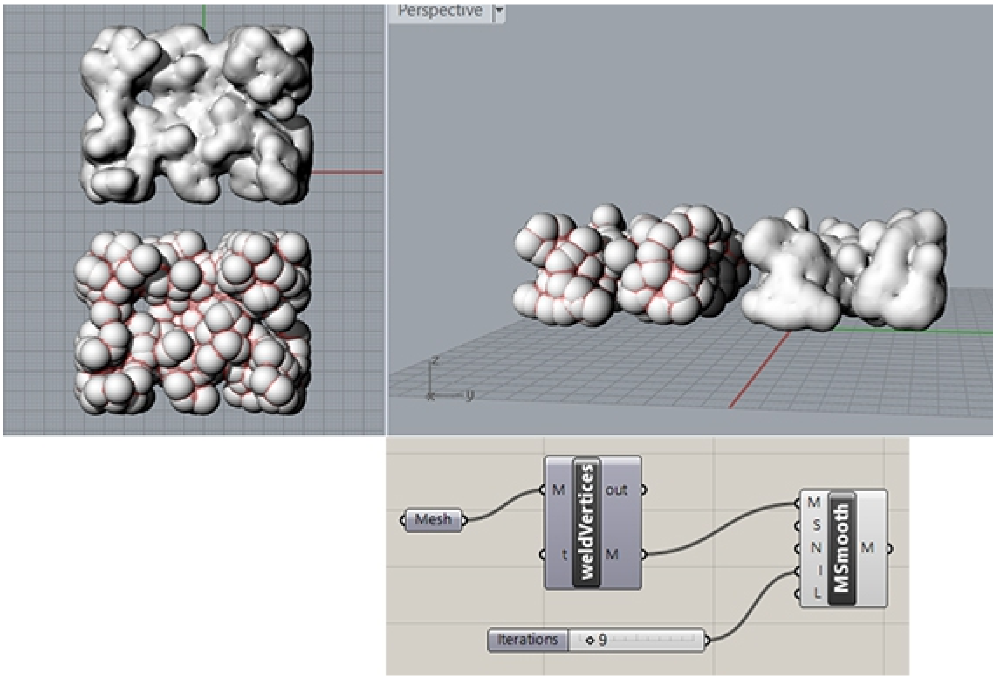


Figure 18: Dynamic data system smoothed model.

An add-on to Grasshopper is Weaverbird; the 'smoothing' component from this add-on can be applied to a mesh or surface. Smoothing is a threshold that rounds clearly defined edges, a level of distortion or noise that can disguise the makeup of entities; noise levels can be adjusted using numerical sliders. The result is akin to smoothing edges with finishing rubbers when working in clay. Applying the smoothing function to the dynamic systems model resulted in fluidity, where the mass of spheres appeared as an inflated uni-body rather than pieced together with multiple spheres.

The CNC machine carved the model from a Matai timber stock, executed in two phases – the top and then the underside. The CNC can have varying-sized drill bits attached, dependent on the scale of the milling; this way sections can be removed with speed. A larger bit will leave traces smaller but similar to the trace of a gauge chisel when carving wood with a mallet. For finishing purposes, a finer drill bit or hand sanding can be used to remove the marks. On completion of the milling process slight texture from the drill bit remained, some areas had chipped because of the direction of the timber grain. The fine traces had created an almost-linear pattern over the z and y axes of the object; the rings of the wood grain interact with these lines, moving the pattern in a rotational direction. To allow chance to play a role we remain open to the idea that attributes unveiled during processes can become valuable to the work, in this instance a new pattern emerged.

Figure 19: Dynamic data system smoothed model. CNC milled Matai timber, 285 x 375 x 160mm.

The Matai timber stock prior to milling had traces of tunnelling created by the Huhu grub.[6] The patterned traces of the drill bit allude to machine manufacture, in juxtaposition are the organic tunnelled tracks left by this large grub, both share the activity of removing timber. A tunnel is defined by two openings, yet the seemingly random path the grub borrows creates a labyrinth, a network of tunnelling. These now burrow into

6 A large beetle, endemic to New Zealand, in its larval form.

the object, where or how deeply they penetrate is not completely revealed.

The three-point axis of the CNC means that no undersides of the forms are carved, this being similar to the drape effect. More smoothing occurred and as a consequence the model from an above view is similar to a 3D cartographical map, in which case the grub cavities could resemble a cave. This isn't conclusive; the form also appears as a moulded bubbly formation, bubbles contain gas and are lightweight, when lifting the actual object it is heavier than anticipated. Choosing a heavy solid material is contrasting to the form, a literal approach would have been to create this 3D print from nylon as it's lightweight and can be hollow, filled with air. The element of contrast and chance afforded in the process has invoked questioning, circumstance has developed an unprecedented form. Some of these questions are relayed to the viewer; involving them in questioning is purposeful in extending their knowledge through invoking their imagination.

Generative

In Grasshopper it's possible to simulate positive and negative charges in physics, to attract or repel other elements (see Appendix F). Forces can be measured through number sliders, as we change the ratio we observe the pushing or pulling of the components within that system. This dynamic generates new form to already organised systems. It is evident now that some aspects of Grasshopper aren't substantially related to analogue sculpting tools. Especially when we invoke the simulation of physics through the CAD environment, interaction through this virtual environment is complex. Understanding these forces is essential to deploying these elements with existing frameworks such as a mesh, curves or points (see Appendix G).

Kangaroo is an add-on for Grasshopper; it also simulates physics triggered by timers. A set of points evenly set out on a base plane, upon starting travels over the object creating trajectory lines (see Appendix H). This is an example of emergence generated through an algorithm. An emergent system-designed algorithm in Grasshopper, it is a modality that can be applied to many other forms.

A variety of mesh surfaces created varied results because the points found gaps between facets and wove their way through the model (see Appendix I). Unified surface models resulted in an even crawl over the object; how closely or not the points follow the model, and when they stop, are settings that can be adjusted. A crawling over a draped surface unveiled a new formation of lines. Once removed from the object crawled over, the lines became contours that together suggested form. Not all results lend themselves well to fabrication, these disconnected elements standing freely in space shown below don't bode well but an attempt could prove interesting.

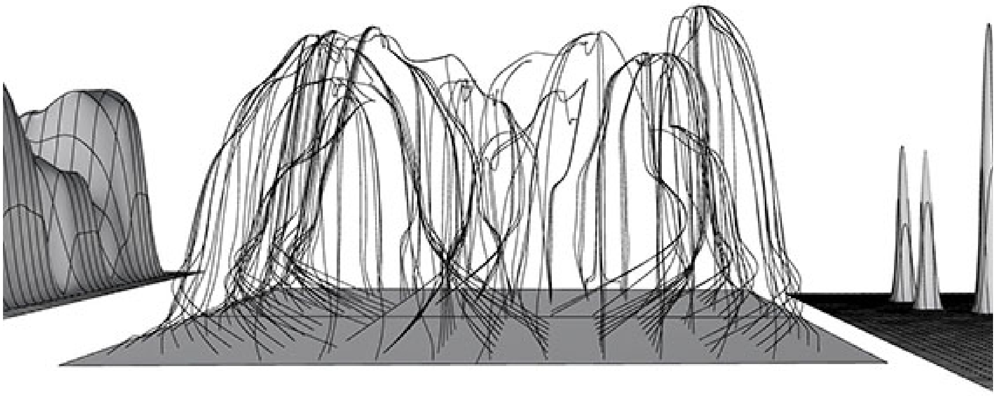


Figure 20: Dynamic data system flow lines model.

Applying process strategies to CAD for the purpose of form finding, we consume time in the process of making, the material we're working with, seemingly infinite, allows for continuous experimentation, not being confined by the expenditure of resource. Mathematical properties inherent to the software are instrumental, creating the potential of finding forms impossible to attain through analogue processing. To fabricate these forms, experimentation transitions creativity and problem solving, stimulating our inventiveness.

'Springs', a Kangaroo component triggered with a timer, relaxes components between anchored points (see Appendix J). As a timer triggers these events, the simulation is animated on the interface. Particularly on an open-ended cuboid form, the mesh relax animation appeared to give the surface material a quality like that of a membrane, such as rubber sheeting or spandex. Preserving this membrane quality challenges the hard rigid materials deployed for fabrication so far. Working in assemblies means there's choice in material beyond what's applicable to 3D printing or CNC milling – materials that may illustrate the simulated physics in Grasshopper or perhaps materials that exhibit being, easy, light, thin, sparse or clear, lyrical to CAD; crafting in material not made of matter.

Modular

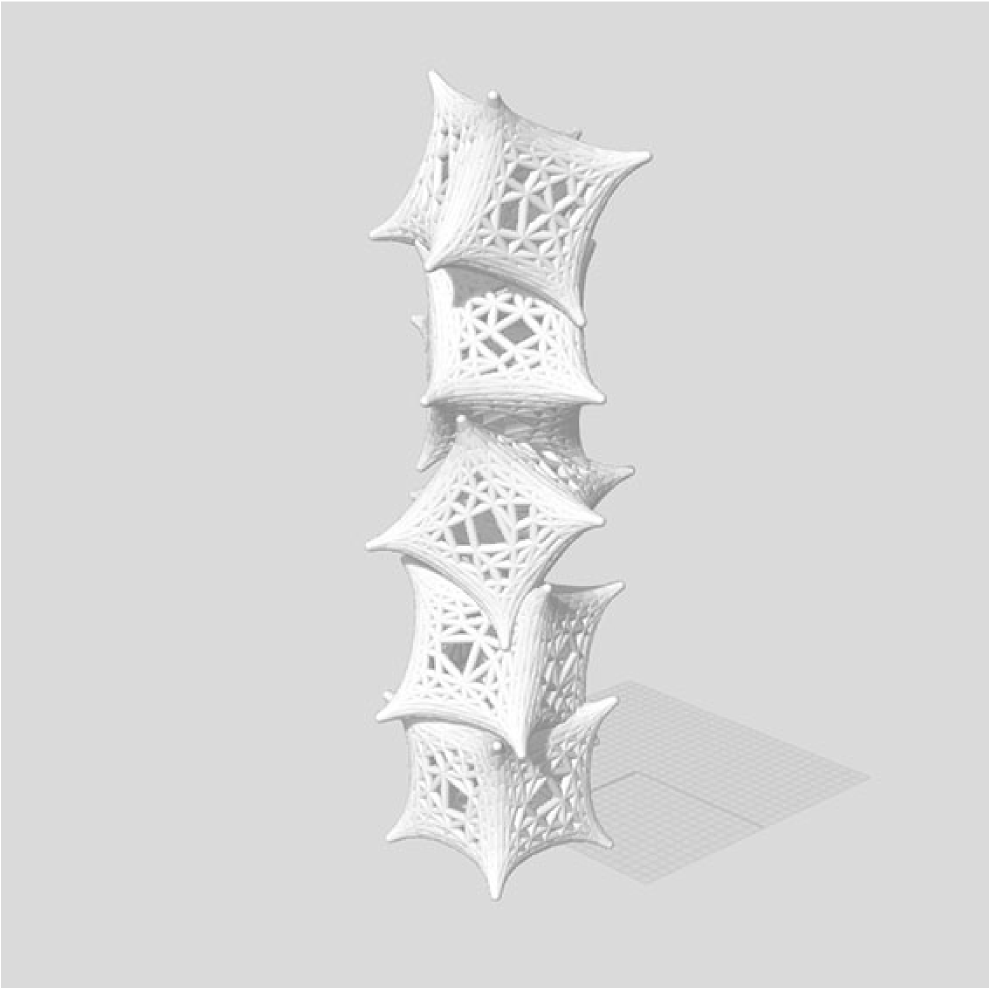


Figure 21: Stacked relaxed mesh cubes.

Connecting a number of components together in Grasshopper can consume a substantial amount of a computer’s processing power. To avoid crashing the system, or time-consuming loads, it's best practice to save work often and experiment in compartments on projects that are more demanding. Bringing them together at the end through carefully plugging components with heavier load times one at a time between saves is recommended.

Through this modular approach we can arrive at complex forms. A series of cubes rotated on both x and y planes travelling vertically along a line: each of these cubes is a suspended relaxed mesh using the 'springs' feature. A mesh subdivision with a thickness for the purpose of 3D printing resulted in a decorative patterning (Figure 21). The software does have its pitfalls, where we can opt for familiar solutions to fabricate, becoming mediocre examples rather than adding qualitative value, demanding that we question why we're applying a feature to the form and how this is consequential.

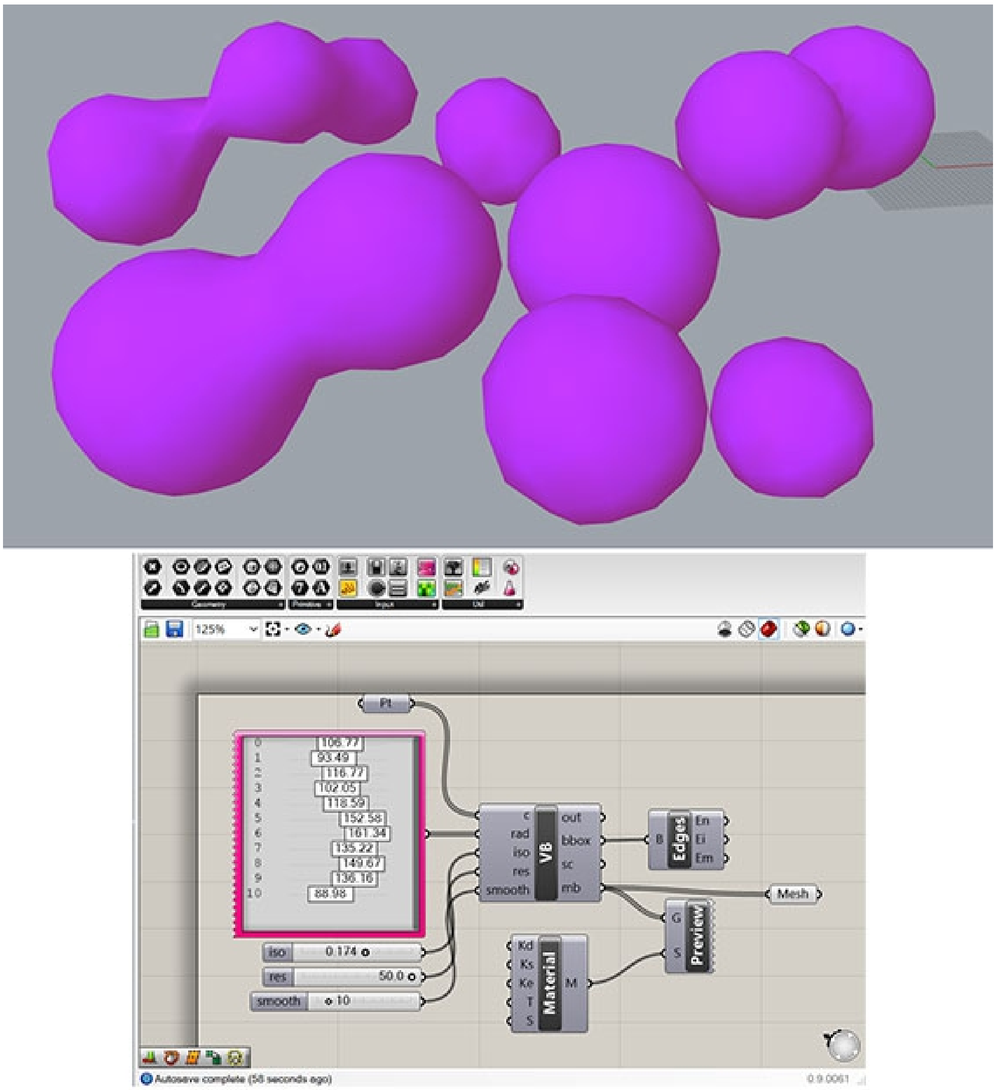


Figure 22: Meta-balls algorithm by Dave Stasiuk.

In any medium the tools and medium dictate the results to a certain extent. It's not by coincidence that a 2D meta-ball function already present in Grasshopper sparks the interest of several users requesting a 3D meta-balls algorithm on my discovery when searching for it on the World Wide Web. Meta-balls depict a morphing of two or more spheres. Adjusting the 'Galapagos' component drives the balls to emerge out of the interface vacuum of space and inflate out of another ball, eventually splitting to a singular entity only to repeat the process. The morphing balls are in a flux of emerging or separating, modelling a universal process that can be identified in an atom’s state of change or the process of birth, as one body emerges out of another.

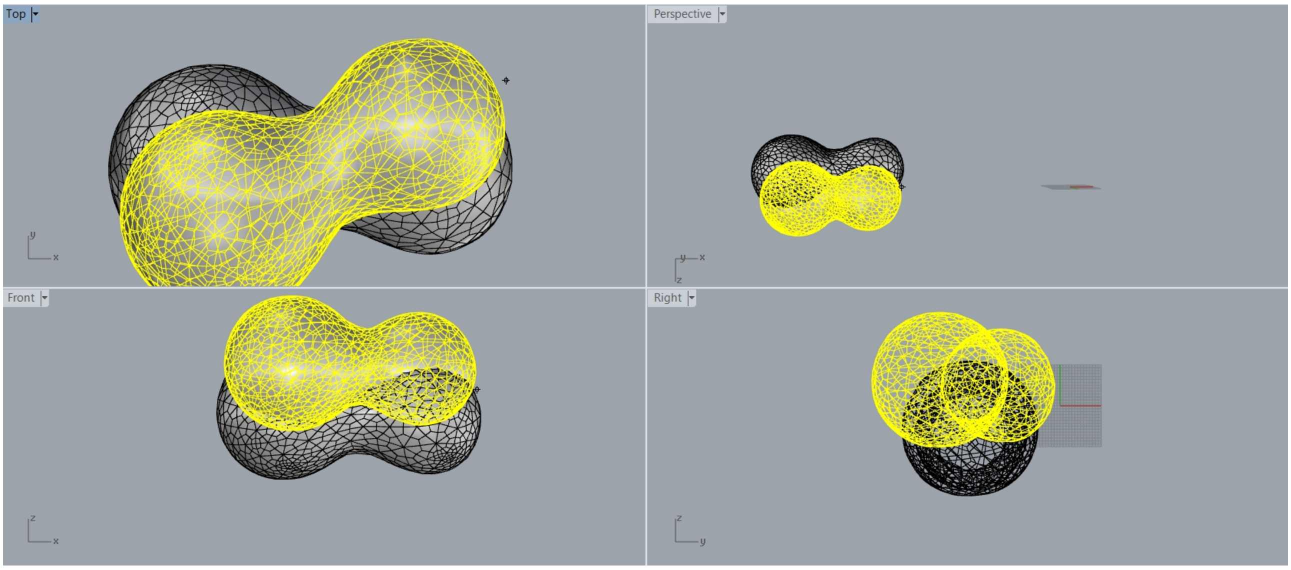


Figure 23: Deduction of meta-balls.

A natural desire is to break open one of the meta-balls and reveal the inside. Through cloning one of the examples, shifting the copy half way up from the original with a slight rotation created, deducting one mesh from the other mesh, what remains is an empty shell. While enough of the original model remains to be perceived as two spheres morphing, the removal of half of the body leaves the shell in a state of change, where it is either becoming or collapsing.

The previous deployment of rotating cubes led to a "relational composition undermining singularity and unity", the meta-balls perhaps were "too consistent and lacking in variation" (Shaw, 2010, p.113). The remaining shell of the meta-balls maintains the sense of whole from multiple viewpoints, yet is varying from these angles, inviting the audience to move around the object. Large-scale work can heighten this sensation, especially when set in a vast landscape like that of Gibbs Farm: works are perceived from kilometres' distance on the horizon, or towering above us and as we elevate our position on the hillside are peered down upon. Walking through the landscape, we are constantly attaining a new viewpoint of the works.

Interpreting the wire mesh in a material, the wire curves can translate into iron rod, fixed with welds at the vertices. However if this object is to be large there will be logistical issues: storage, transport and if built in a workshop it will need to fit through the doors. Therefore a modular assembly is decided on, where the mesh curves are connected at the vertices using a 3D printed plug-and-socket system. The iron is substituted with extruded aluminium tube: it is lightweight, strong and flexible, properties inherent to nylon printed parts too. The tubes serve to be a socket for the nylon 3D printed parts.

Along the curves of the mesh the mid-point between the curve beginning and end is selected and divided in two again from the mid point to the ends. Applying the pipe function, a thickness is added modelling the basic principle of the nylon parts (see Appendix K). To maintain a smooth mesh topology suggestive of the meta-balls form, Weaverbird mesh subdivisions can create density and geometric patterns that vary from standard mesh triangulation. The Catmull Clark subdivision is decided on, taking on a flower formation where the eye is lead to the centre and out again creating a movement over numerical geometries divisible by four, five, six, seven and eight over the terrain of the object's mesh.

To understand how many curves and vertices are contained in the model, a designed algorithm calculates the metrics and lists them on a panel. In total there are over 5000 vertices and curves, meaning the assembly consists of too many parts. Reworking the model through simplifying the mesh before adding the subdivision means a compromise between number of parts and mesh density can be found, where the total number of components comes to under 1500 (Figure 24). Each part is unique; therefore a numbering system is required, parts look similar to one another and there are many.

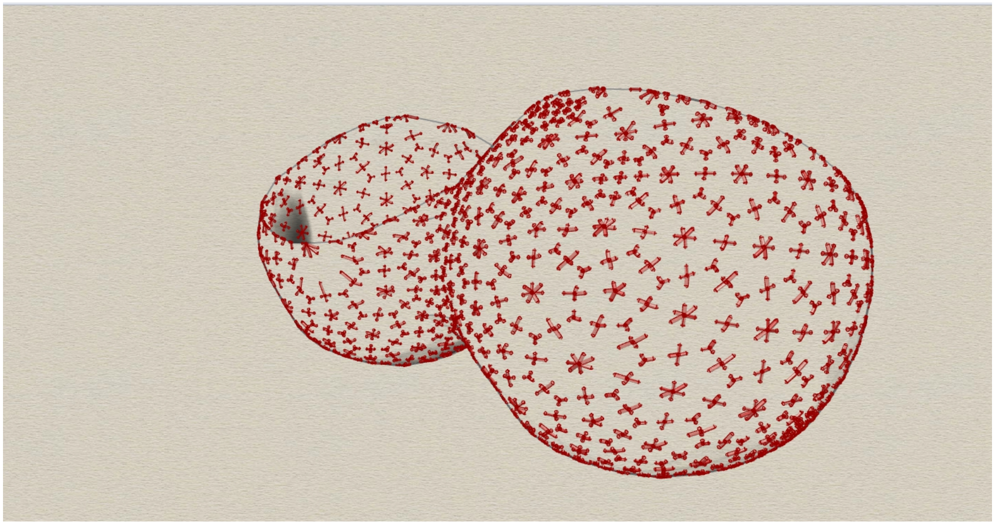


Figure 24: Meta-balls with Catmull Clark subdivision.

A list of each curve length numbered can be extracted. These, along with the numbers of the vertices, are visible on the model, requiring problem-solving skills and logic to comprehend the figures; to number the actual objects is challenging. Time is spent crawling through the Grasshopper forum for a solution, before realising this to be a problem-solving task. Fab Tools, another add-on for Grasshopper, is used in combination with vectors (see Appendix L), in order to project the number on the part and deduct the extruded number mesh from the parts mesh, great care being taken to minimise the size of the number down to the millimetre. Displaying the numbers on the inside of the mesh meant they read back to front: the task of matching the part seems daunting let alone having to do it back to front.

Displaying numbers on the outside of the mesh on the 3D printed parts meant the possibility remained to sand them down after assembly. However, it was decided the numbers were to remain as part of the work, being a mathematical model, essentially numbers. As the pitted marks of the chisel indicate the tooling used while fabricating timber, now numbered 3D printed parts remain honest to the method of construction (Figure 25).

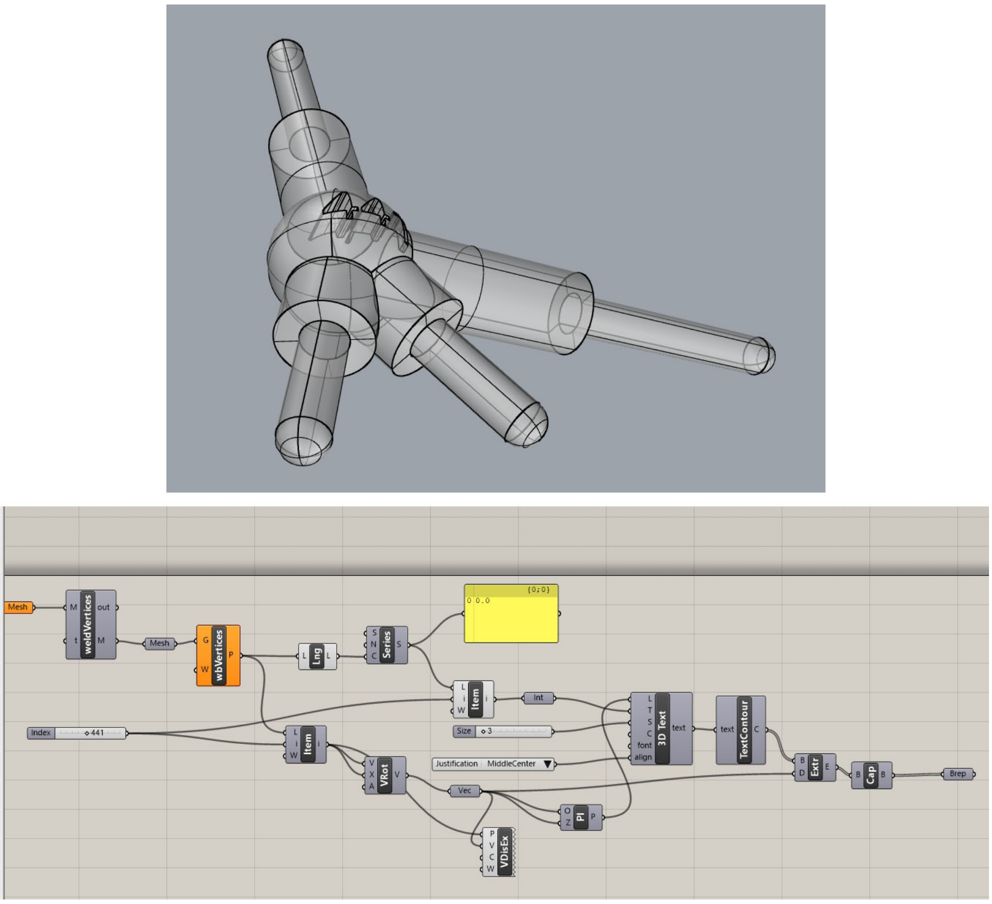


Figure 25: Part #448 with number perforation.

Initially the idea was to textile dye the 3D printed parts and colour the aluminium in the same colour through anodising. Instead it was decided to create distinction between the parts by anodising the aluminium a colour, dark blue, and leaving the 3D printed parts white. This further creates a patterning over the mesh that becomes part of the rhythm created by the Catmull Clark subdivision. New patterns emerge and against a white gallery wall, the white 3D printed parts blend into the background, creating a suspended network of dark blue lines suggesting form (Figure 26). Or in an outdoor environment the dark blue lines fade into the darkness of the night sky with the 3D printed parts standing out when slightly lit by the moon, creating an effect similar to the simulation of CAD, where models appear to be suspended in space.

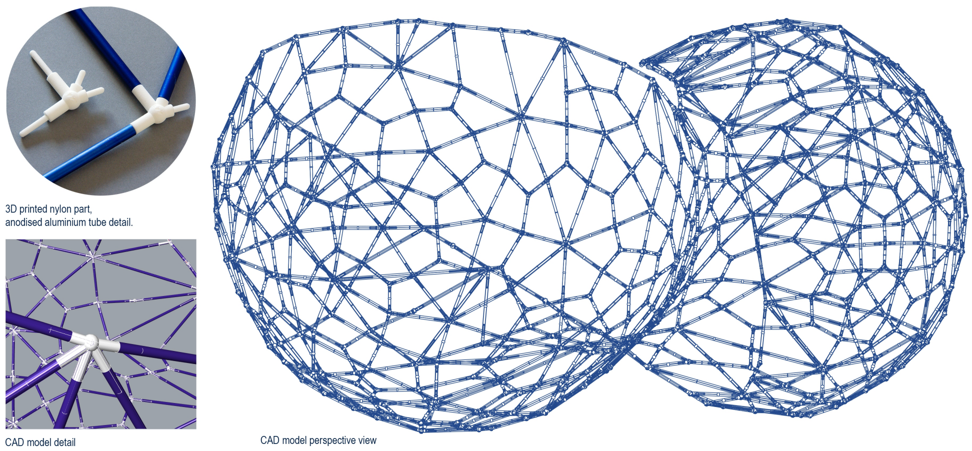


Figure 26: Mockup illustrating anodised blue aluminium and white nylon colour combination.

The scale of the model is comprehensible as functions are performed on the individual parts; for if it's not the individual numbers set on the 449 parts or the boolean union performed on the set of surfaces that make up a part (see Appendix M). The scope of the project became evident stacking each part in columns and rows almost touching but maintaining a 2mm spacing between each and every part, turning individual parts from two elevations so they remained flat (see Appendix N). Fortunately spacing can be effectively deployed with functions that group objects from small to large, in a column with an equal distance from one another.

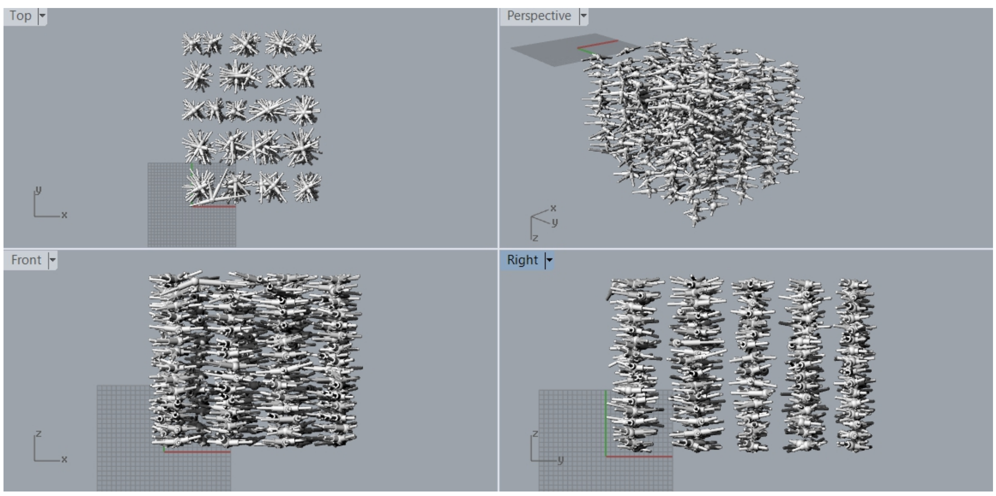
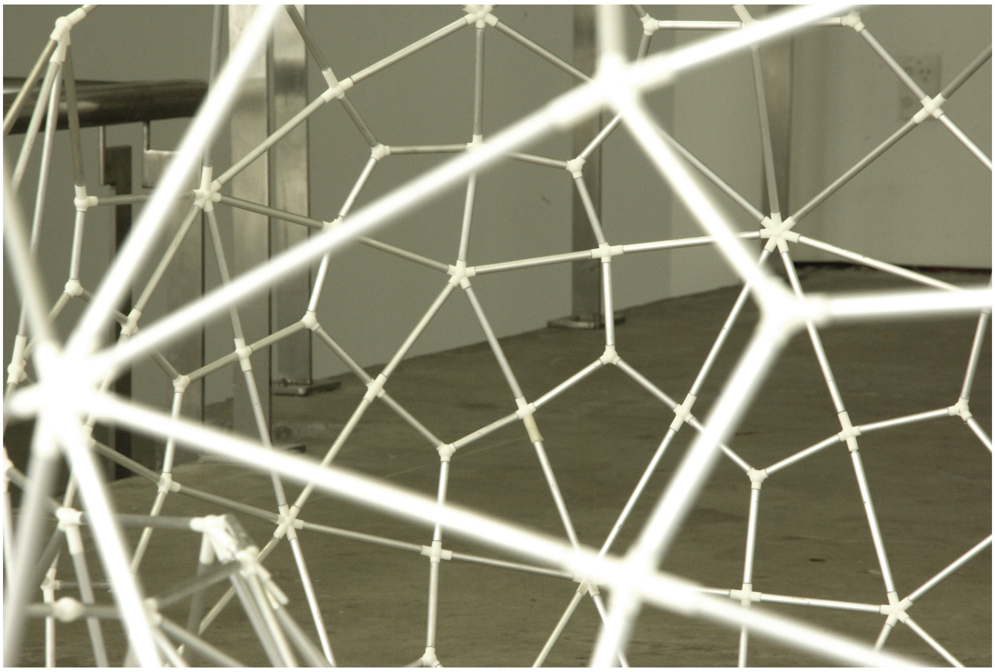


Figure 27: Parts stacked into a cube format ready for 3D printing.

The studio environment changed from the virtual interface-based click environment to an actual bench top where the data (lengths) collected from the model was applied to the aluminium tubing. A set of varying pipe lengths stretching 80 meters of pipe about to be cut into over 900 lengths. Each piece of pipe being of millimetres precision once cut showed a rough and at times crooked edge. Finishing with a power file each pipe marked and labelled to create a straight smooth edge in cohesion with the 3D printed parts becomes an action performed over 1800 times as each pipe has two sides. At this stage the smaller pieces of metal become hot as the friction of the sand paper heats the aluminium. The precisely fabricated aesthetic of extruded pipe and 3D printing meant the emergence of a rough edge on the pipe to be detrimental to its final appearance.

Both 3D printed and aluminium tube components are best grouped by their numbers in bags in preparation for the assembly (see Appendix O). Evident in the space of several hours assembling the components through referencing the CAD model on the interface is the force of gravity as these parts take the curvature form of the model. A calculation of .5 of a millimetre thicker 3D printed part to fit better in the aluminium pipe could possibly have meant the absence of glue used during this process. The nylon material of the 3D printed part weakened the work, with glue as bonding agent manoeuvring the form proved difficult (Figure 28). The idea of a modular assembly that can be constructed and deconstructed for transportation is relative to the ease of assembly, in this case the amount of bespoke parts means the activity is labour intensive to the degree where a small group is needed to build the work. The object served as a prototype, the next version will be made of 3D printed metal. Replacing bonding agents with a mechanism will also be considered and tested prior to the next build.



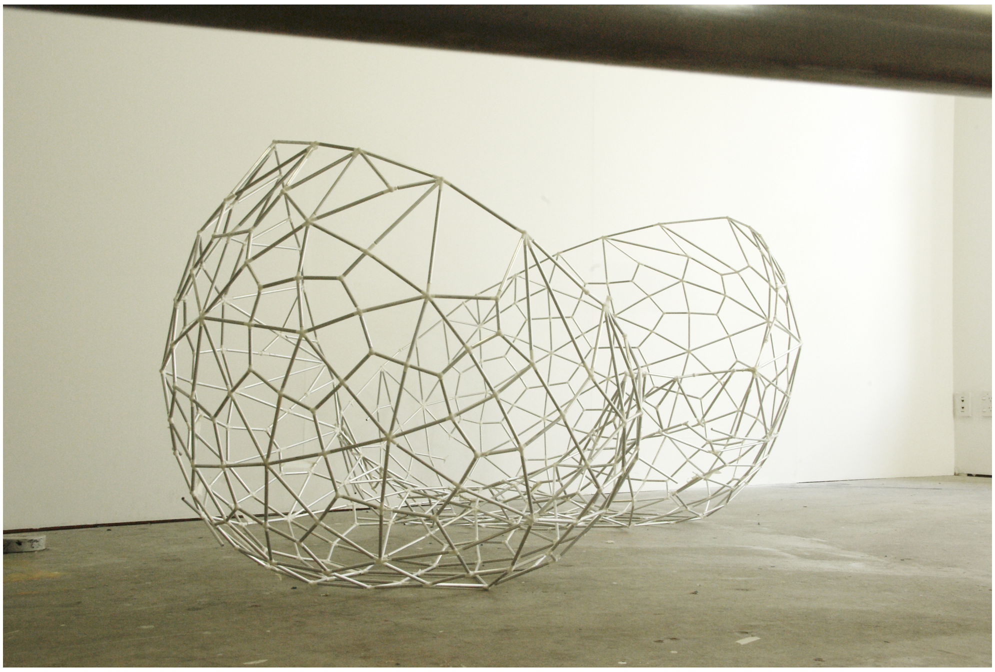


Figure 28: Meta-pattern 3D printed nylon and aluminium tube, 1800 x 1200 x 1200mm.

Conclusion

In the early stages of this research Grasshopper's modular interface seemingly offered an environment in which anything could be made from graphic components. The engagement with this 'fresh' medium is not unlike our first childhood experience of discovering painting, where few understand the boundaries of the canvas. Grasshopper's modularity is akin for those who knew about Lego, where we could make anything from those modular plastic blocks.

By avoiding using CAD to reproduce a preconceived design we are able to see past its limitation. Our imaginations begin to run riot with the Lego like plastic blocks, and we quickly forget about the artificial CAD interface. We understand everything we're working with to be reducible by numbers. So patterns emerge and structures occur naturally as we compile geometries. Data structures themselves have a likelihood of containing emergent properties within their system and can be visualised in 3D through CAD and CAM. Arriving at organic forms and watching lines crawling over a CAD object is similar to viewing a time-lapsed photographic animation of a plant growing against a rock face. It becomes evident that numbers, algorithms and data are a medium that is not removed from the natural world despite the CAD environment being perceived as artificial.

In this age of data collection, systems that visualise data as 3D digital models can be actualised through CAM or by modular fabrication techniques that remain faithful to CAD/CAM. CAD systems such as Grasshopper that can integrate data from other software such as Processing and Arduino enable direct sensory input, and open up the potential for generation of environmentally responsive CAD form.

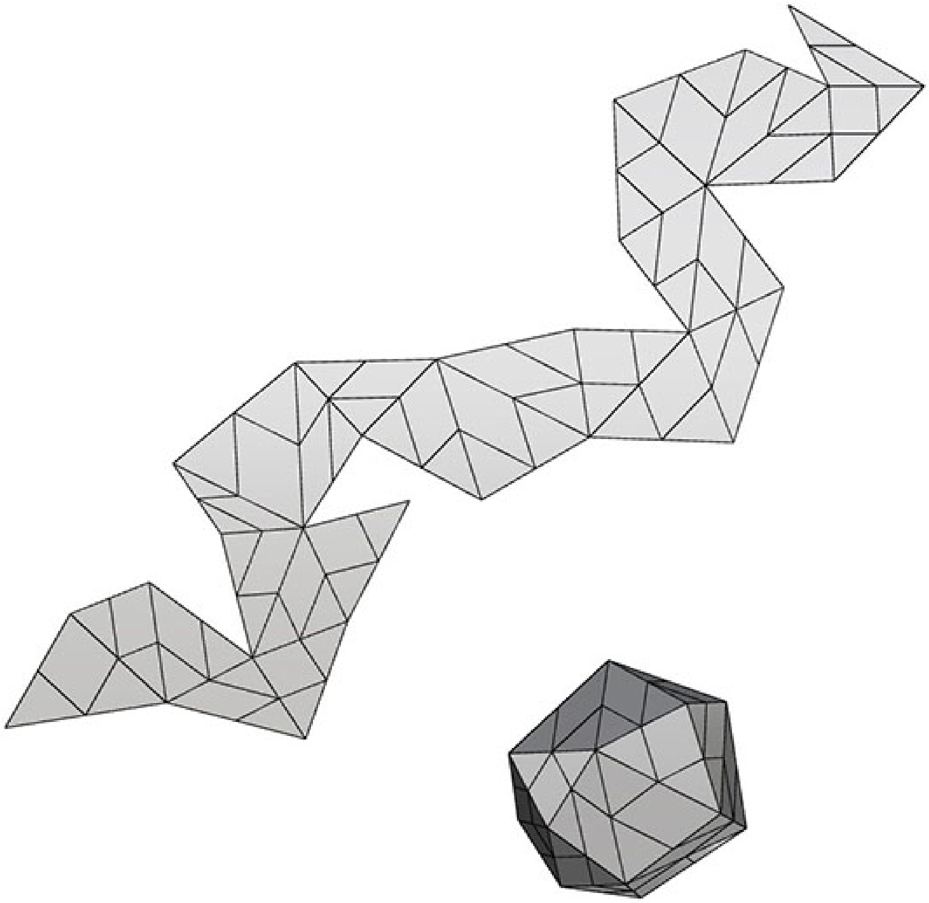
CAD techniques such as *unfolding* forms, parallel emergent material strategies such as accident and chance that are present in CAM processes. However further processes explained as being understood through tacit knowledge render themselves obsolete through the virtual interface of CAD. Despite the pervasiveness of technology, analogue sculpting remains a viable means of *finding* 3D form. While not yet a replacement for manual approaches, CAD/CAM methods. influence, enhance and develop existing methods of sculpting these media indirectly through agents such as ourselves.

As the sword maker tempers the steel from cold to hot with just the right amount of force, computers temper operators. Performing the software to his/her perception, these tasks are often a compromise, or negotiated through finding work-arounds within the system. Assembling large forms from a collection of modular parts offers the ability to exceed the limits of standard 3D print envelopes. Such digital modules have the possibility of being applied to a variety of models. In this sense the investment of time spent designing modules is offset by assembling a series of forms in a similar fashion. However applying modules to forms can ultimately demand monotonous tasks. Such repetitive tasks that are frequently part of sculptural fabrication processes, offer little creative potential and can be readily preformed by modular CAD design approaches. However designing efficient modulations, balancing scale and number of parts, exposes us to the risk of embodying CAD and is to be carefully considered.

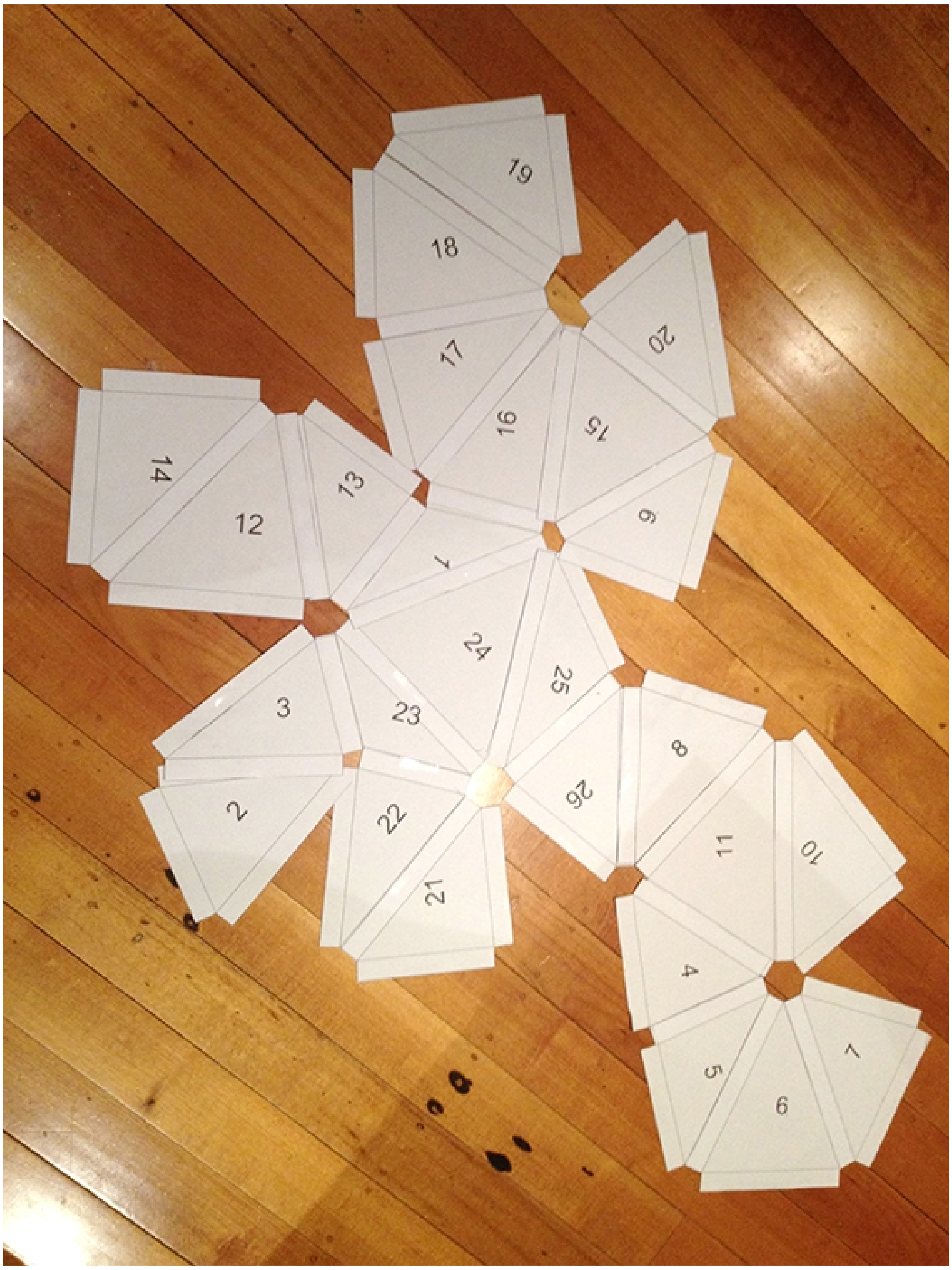
When working with multiple parts, it's easier to manage assembling them when these parts are the same in size and shape, yet mathematically generated forms do not inherit the simplified structure we may identify with basic mathematical geometries. Algorithmic modules output in the Meta-balls structure is made up of parts that look similar but are in fact unique in form. Each part has a specific placement within the structure like that of a piece in a puzzle. Such a modular makeup isn't an efficient method to assembly. When form is complex, whether generated by an algorithm or through playful interaction in CAD, we can negotiate the modular makeup of that form to be a genotype of parts, where a higher percentage are the same in size and shape allowing for the mass build to be assembled with greater ease.

Appendices

Appendix A: Surface unroll pattern.

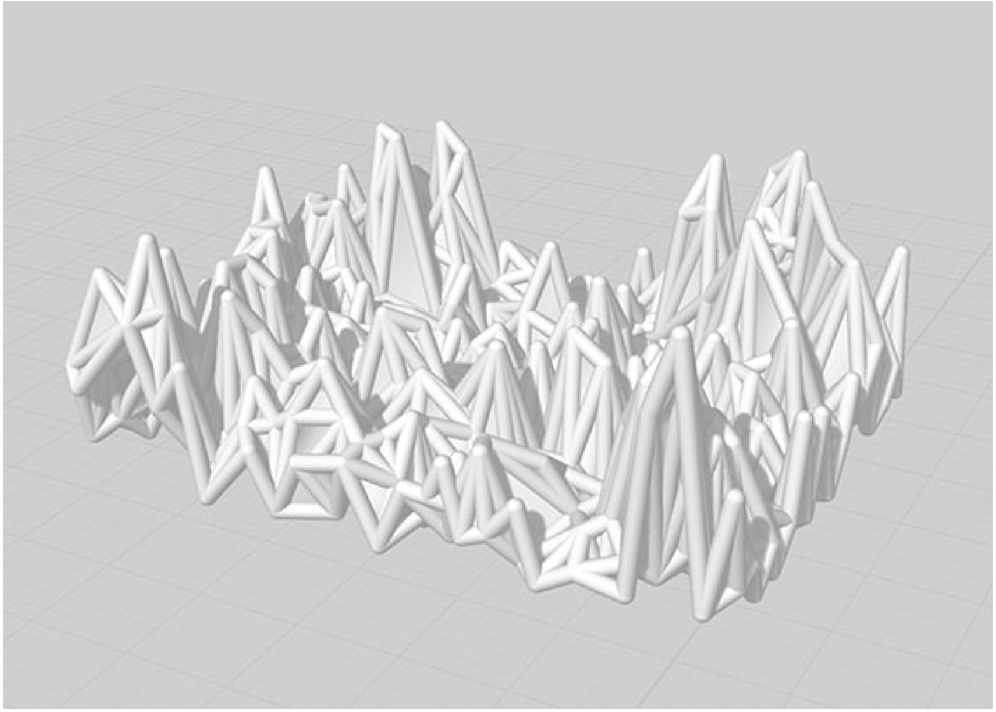


Appendix B: Numbered pattern for fabrication assembly.

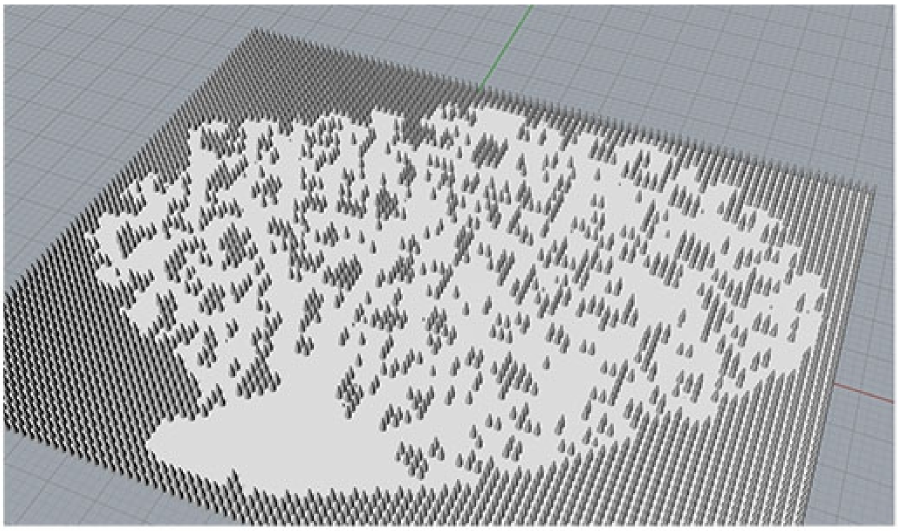


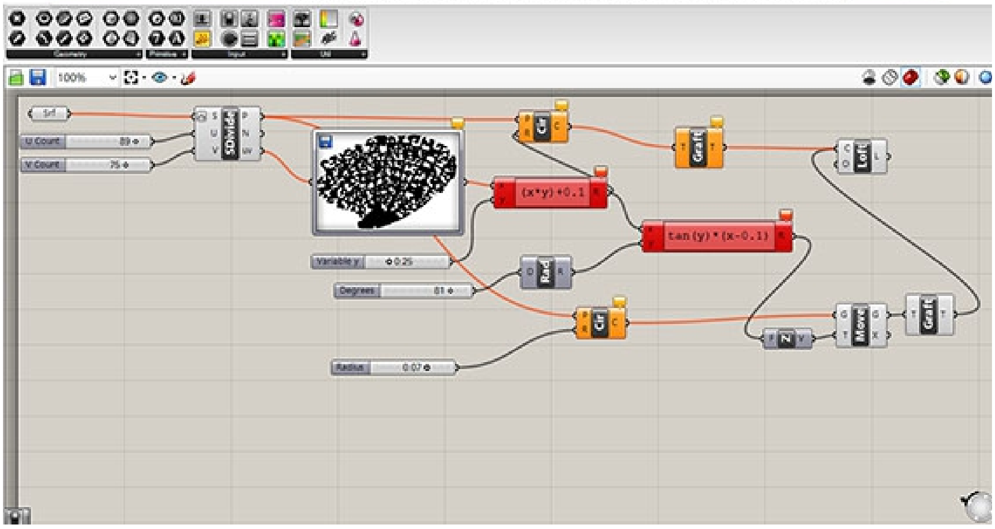
Appendix C: Proposal renderings for NZ Sculpture Onshore 2012.

Appendix D: Dynamic data system with pipe function.

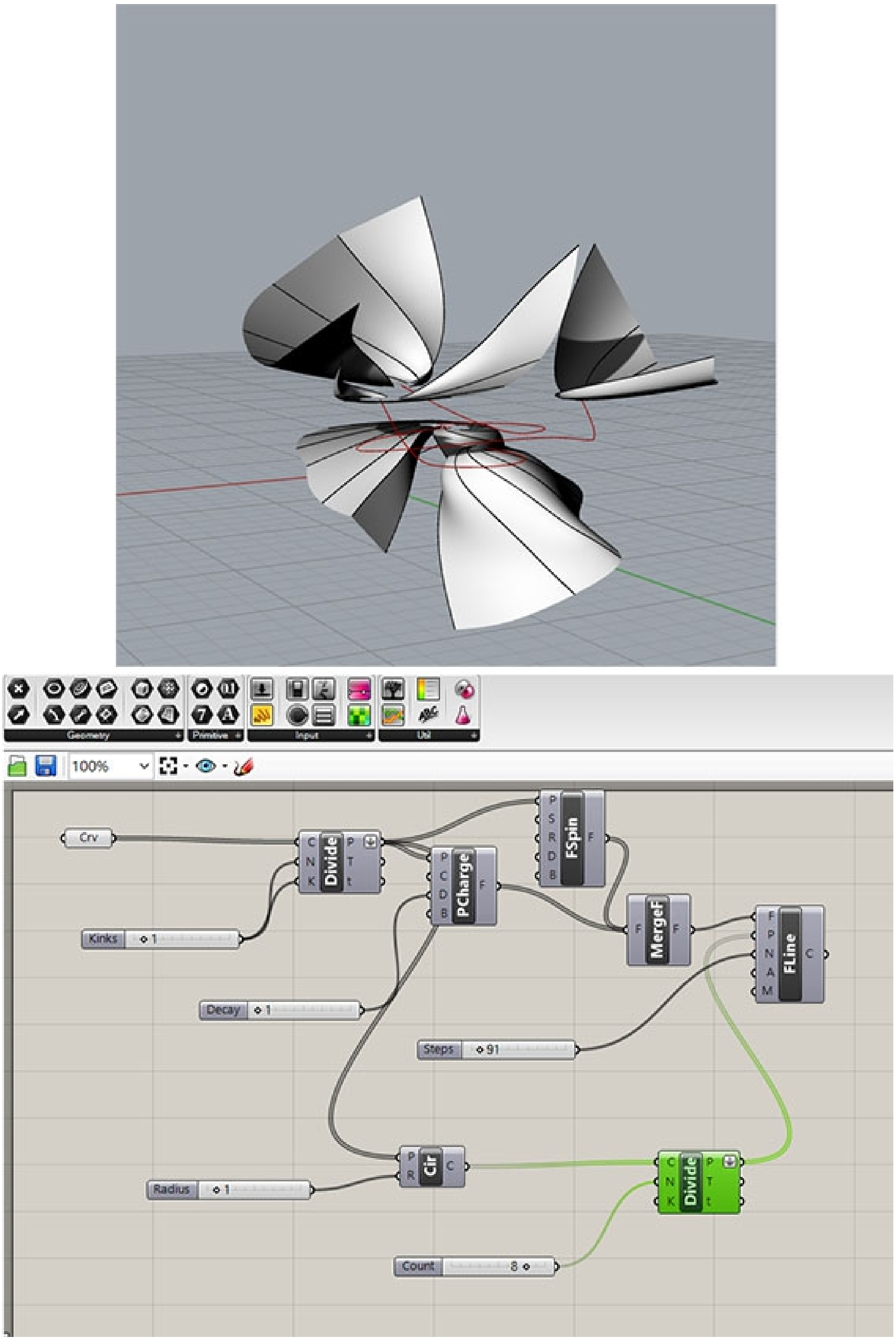


Appendix E: Image processing definition, developed from the Studio Air Tutorials

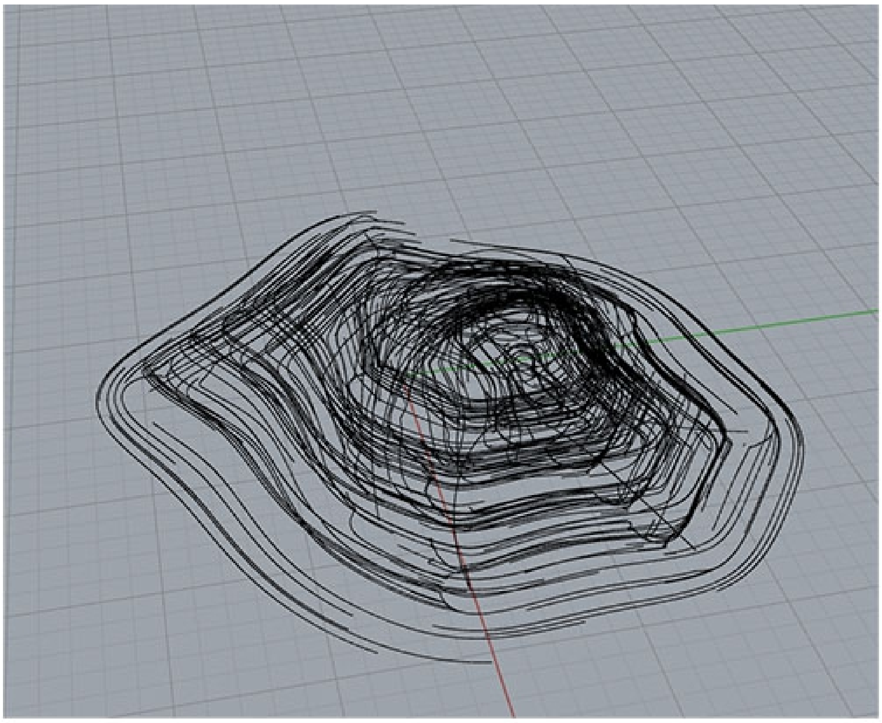


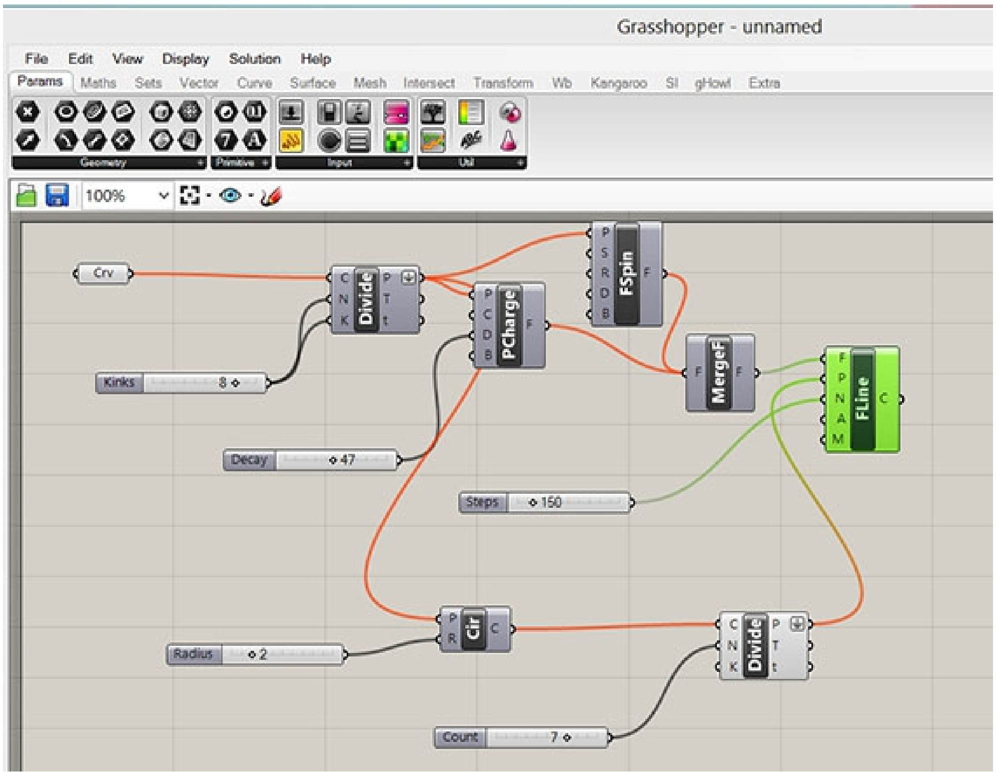


Appendix F: Positive and negative charges definition, developed from the Studio Air tutorials.

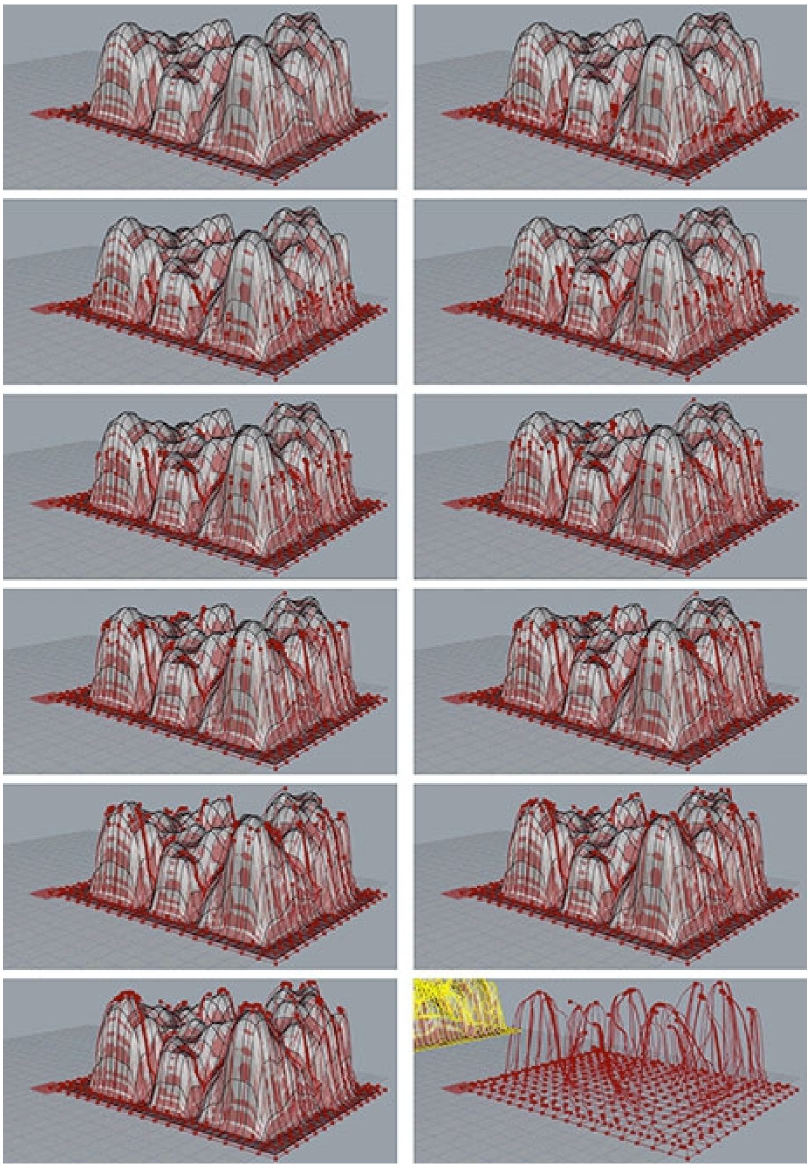


Appendix G: Positive and negative charges definition, developed from the Studio Air tutorials, incorrect implementation.

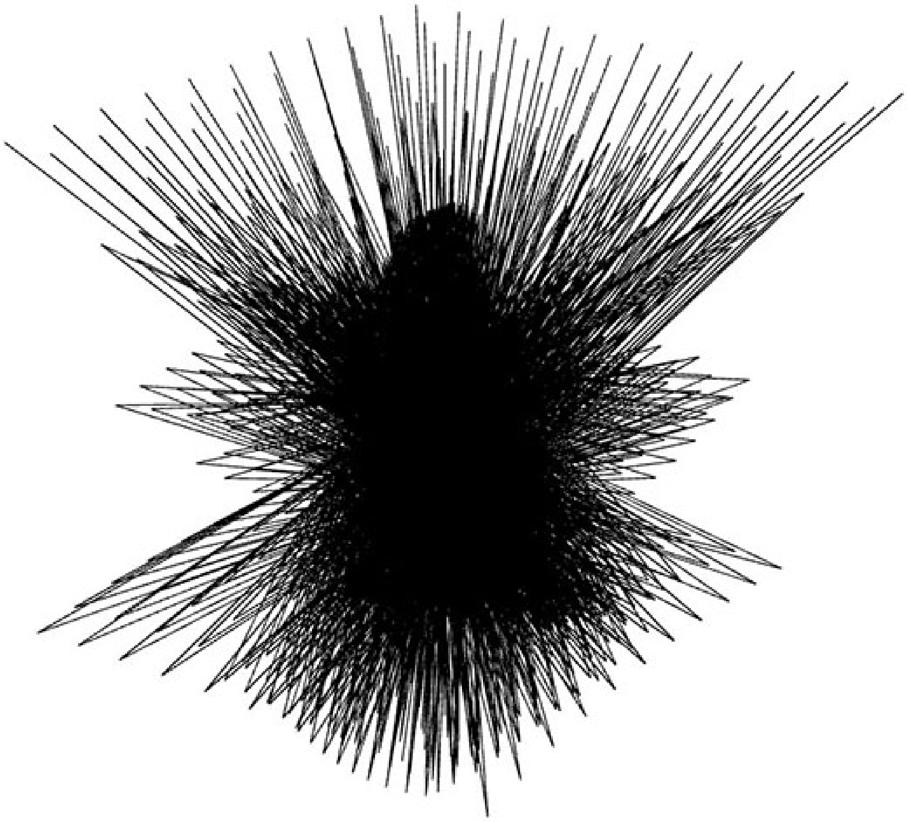




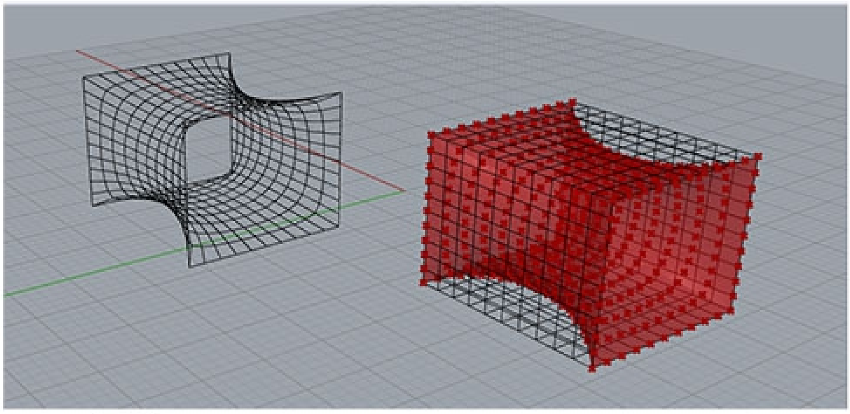
Appendix H: Crawling definition, developed from the Studio Air tutorials.

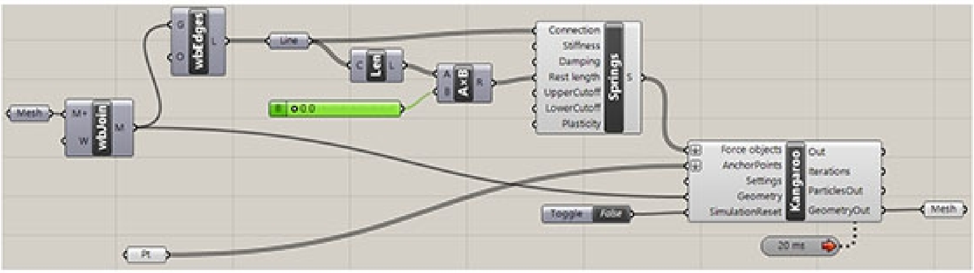


Appendix I: Crawling definition, unexpected result.

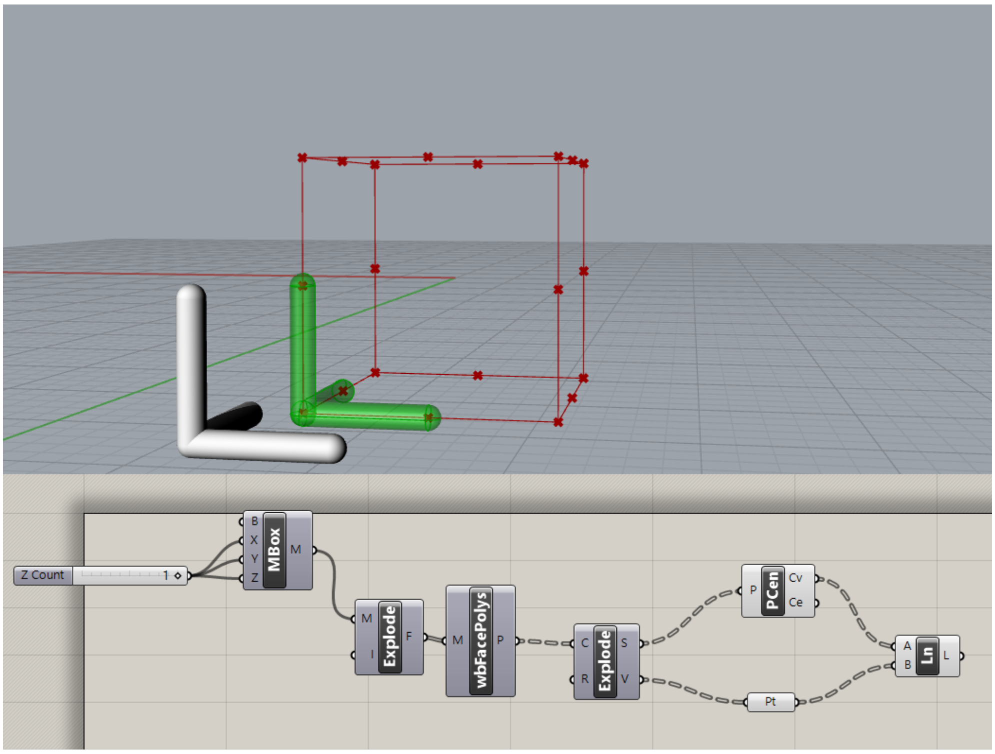


Appendix J: Relaxed mesh definition, developed from the Studio Air tutorials.

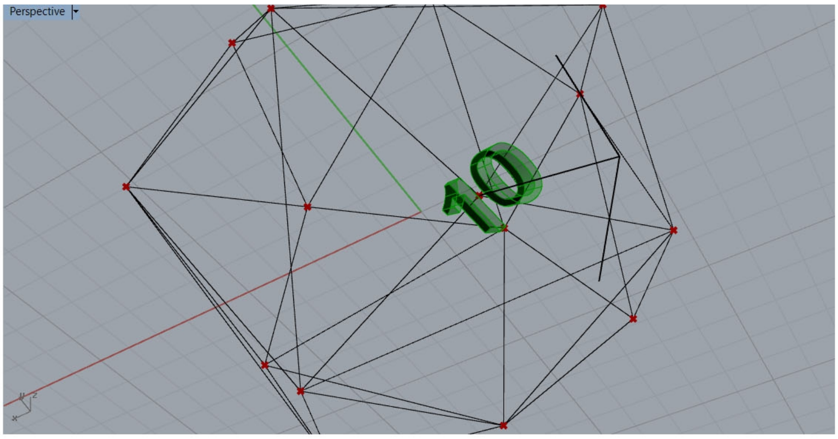


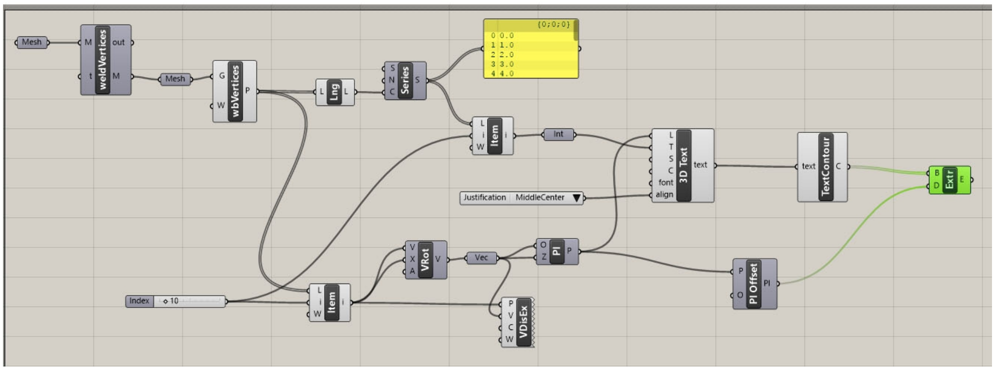


Appendix K: Mid point between two vertices with pipe function.

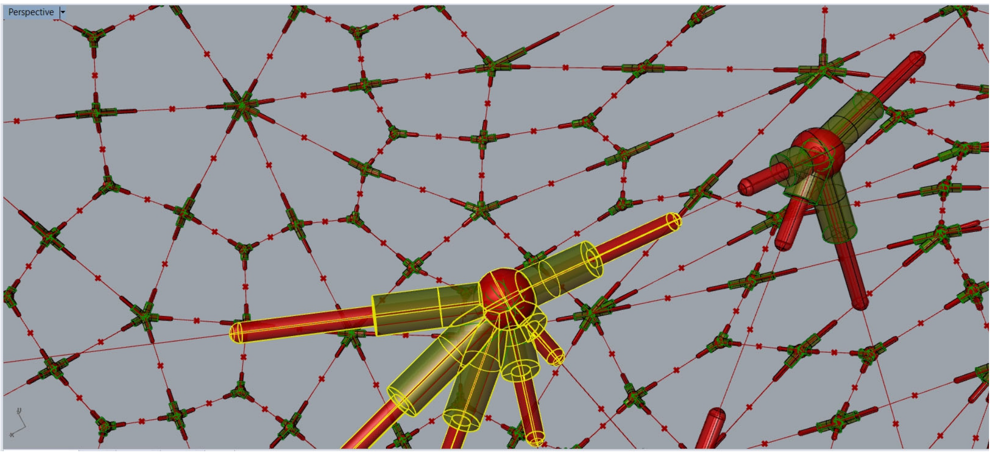


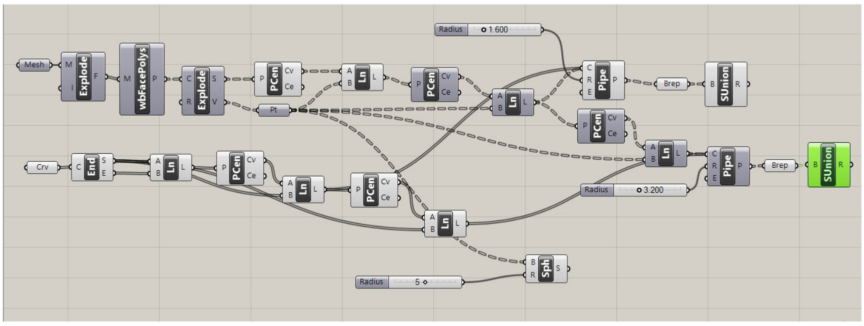
Appendix L: Vertex number projected along a vector and extruded.



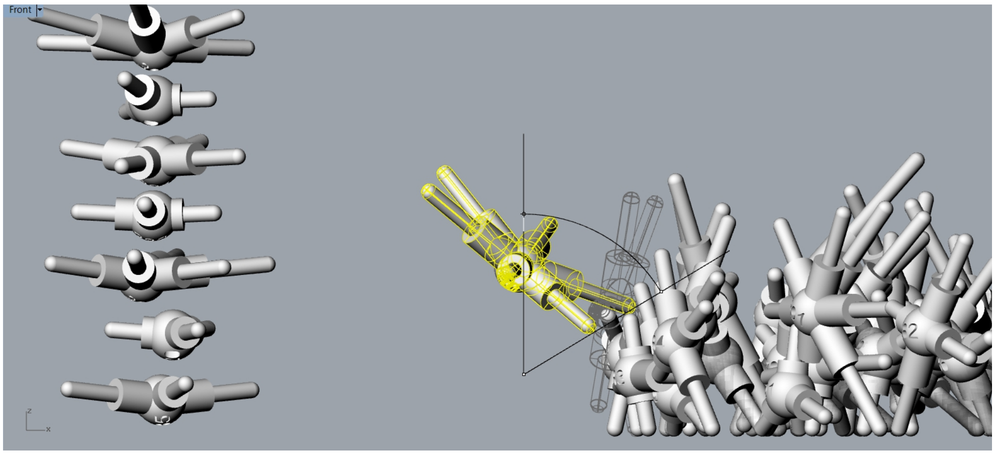


Appendix M: Parts definition illustrating componentry make up.





Appendix N: Stacking parts through the CAD interface.



Appendix 0: 3D printed parts unsorted.

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