Computational Design with Reused Materials

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Abstract Non-standard tiles of slate stone salvaged from roofs of buildings are extremely seasoned due to weathering processes that chip away the weaker bits of foliated rock but are highly variable in their geometry in an unprocessed state. With so much current attention being focused on free-form geometries and procedural methods for vaulting, this paper proposes a translation of building with found materials into a digital process whereby the waste pieces of slate stone are scanned and a database is established wherein the found-forms of slate stone are catalogued and digital representations of the same are created. Organizing the found forms, explores the nesting and consequent stacking of the pieces together thus defining a boundary surface. The boundary surface is subjected to a form finding process using the particle-spring system giving rise to a funicular form. The pieces are then oriented from the boundary surface onto the funicular form without any overlap. The relationship of one piece to another is explored by means of milled timber connections in the form of a structural arrangement by triangulating the axes of connections using the centers of each individual piece of slate stone ensuring rigidity of the structure. Assembly of the prototype discusses ways in which these complex materials are brought together – informed by a 3D model, but performed manually. The resulting prototype shell structure is composed of randomly shaped planar pieces of stone connected to each other with wood joints. This exciting potential of architecture developed from a unique interaction of used materials with new technologies and traditional craftsmanship suggests that future application and research in reusing construction waste can be a sustainable as well as a pragmatic design approach.


I. INTRODUCTION

Construction and Demolition Waste (CDW) is one of the heaviest and most voluminous of all waste types. CDW recovery rates are currently only 30-35% but should have at least doubled by 2020 if the targets of the Waste Framework Directive (2008/98/EC) are to be achieved. It accounts for 34.7% of all waste generated in the EU and consists of numerous materials. 75% is comprised of soil & aggregates with around 24% being concrete tiles, bricks & ceramics whereas the remainder 1% accounts for gypsum, wood, glass, metals, plastic, solvents and asbestos many of which can be recycled. CDW has been identified as a priority waste stream by the European Union. There is a high potential for recycling and re-use of CDW since some of its components have a high resource value. Technology for the separation and recovery of construction and demolition waste is well established, readily accessible and in general inexpensive. One of the objectives of the Waste Framework Directive (2008/98/EC) [14] is to provide a framework for moving towards a European recycling society with a high level of resource efficiency. In particular, Article 11.2 stipulates that "Member States shall take the necessary measures designed to achieve that by 2020 a minimum of 70% (by weight) of non-hazardous construction and demolition waste excluding naturally occurring material shall be prepared for re-use, recycled or undergo other material recovery." Despite its potential, the level of recycling and material recovery of CDW (European Commission, 2011) varies greatly - between less than 10% and over 90% - across the Union. But much of this waste can be reused - if we can identify and classify it [17]. In this era of big data, design in every field is driven by data. Architecture also follows this trend, in many ways, by using quantifiable environmental data to obtain optimal building performance, structural data for form finding and elaborate...
financial data for optimizing costs of the project; data is even used to develop creative complex geometric forms. Architecture as a field has embraced data and has intertwined its use within the design process at nearly every stage. However, decisions in design and construction regulating reuse of building waste has not still evolved to the level it should be at and relies on environmentally impacting backfilling since its easy and cost effective.

Also, buildings’ actual lifespan is often shorter than their design lifespan. Changing land values, lack of suitability to current needs and lack of maintenance of non-structural elements often leads to demolition of the building, leading to a more significant percentage of carbon emissions due to construction and demolition compared to emissions due to operation. Imagine if a building was designed from the onset to be able to undergo deconstruction such that a majority of its materials could be salvaged thus designing not only from salvaged materials, but also for future disassembly of built forms such that the constituent materials can be reused. Additionally, the main advantage of building with salvaged materials is that they benefit from the high technology used for their creation in the first place. So, it only makes sense if we rethink how we reintroduce them into the product lifecycle chain.

Adaptive reuse is a philosophy from which the creation of this project has been derived. This requires an inversion of the design process where you create from an available database of materials thus reusing waste and adding to its life cycle [1] rather than just recycling. It results in a design that reflects and heroes the material since the design is adapted with respect to it. A source of inspiration is Architect Kengo Kuma who intrinsically weaves natural materials and their characteristics into the design and spatial fabric. Another inspiring artist who creates design from salvaged material by creating intrinsic linkages between them is El Anatsui.

“...I have experimented with quite a few materials. I also work with material that has witnessed and encountered a lot of touch and human use... and these kinds of material and work have more charge than material/work that I had done with machines. Art grows out of each particular situation, and I believe that artists are better off working with whatever their environment throws up. – El Anatsui, 2003.”

Moreover, a number of recent research projects have investigated the use of raw materials in digital design and fabrication workflows, such as the arrangement and positioning of irregular wood components through algorithmic techniques (Monier et al. 2013) [10]. Further studies show the possibility to physically scan and data process natural wood branches (Schindler et al. 2014) [27] and connect them by organizing the forms obtained within the dataset and optimizing their placement with respect to the global geometry [6]. Mine the Scrap Project [17] uses an enhanced stream from any webcam which identifies and classifies the scrap you have collected for reuse. The target design is dynamically adapted according to available scanned material. Whereas, robotic fabrication techniques for material of unknown geometry considers an overview of all the above-mentioned workflows in order to produce a double story timber structure with hand split wood plates of varying dimensions (Eversmann. 2017) [9]. These new design processes allow for greater complexity in the material stock, reducing the energy costs associated with recycling. A greater complexity in material stock can be tackled with far more ease with the help of the computational tools and data that are at our disposal. With the advent of the above-mentioned digital tools, fabrication techniques into Architecture and the Building industry, it is well within the scope to scan potentially reusable waste materials and input them into a digital platform in order to be able to access its dimensions, material properties, physical characteristics etc. so as to reintroduce them in the design/construction process and make them available to designers and builders to facilitate new construction. Some current trends can be associated with Material Resources that deal with cataloguing and reselling materials/products for reuse e.g. Rotor Deconstruction [22] in Belgium is a pioneering company in the field of salvaged building components. The team dismantles, conditions and sells materials, as well as helping building owners, contractors and architects on the subject. Matabase [19] & Resourcerie des Biscottes [21] in France to name a few works on
similar principles too with primary focus on all kinds of day-to-day house-hold products.

Thus, the aim of this research is to form a workflow wherein we can ease the process of linking salvaged materials of various shapes and sizes so as to form a cohesive and systematic assembly process that can be tweaked with respect to different design iterations. The objective is to use the idea of a material resource, by identifying potential materials that can be re-inserted into the product life cycle chain, initially not in a physical way but in the form of a virtual database that identifies all the characteristics of the material such that it can be input into a digital modelling software to analyze, modify and reapply to a new design application.

The paper has been further categorized into the following sections: Section 2 describes in detail the process for the envisioning and implementation of the design and construction of the prototype. Section 3 details the assembly process of the prototype. Section 4 presents the inferences from scanning, computation and fabrication of the prototype as well as problems faced in the process. It also includes a brief description on other observations with respect to the prototype. Section 5 delves into additional experiments carried out using the same principle but completely different strategies post the scanning of the pieces. Section 6 addresses the conclusions derived from this research and different paths for the way forward. Finally, section 7 lists and describes all the tools and plugins used for this research.

II. METHODOLOGY

The process of design and digital fabrication of the prototype shell structure out of reused slate stone and wood connections can be broken down into 7 essential steps from identifying the material to work with, scanning it, stacking the pieces together, defining a boundary mesh, giving rise to a funicular shape form the boundary mesh, orienting the pieces on the funicular form, designing and defining the connections and lastly, carrying out a structural analysis to check the displacement under load, if the stone pieces and connections are in compression or tension and if the pieces of stone can withstand said forces.

Process - Pictorial Flowchart

Defined here (Fig. 2.0.) are the iterations to each step of the process to configure the best possible design solution. Numerous iterations with respect to the stacking algorithm for the pieces resulting in different funicular forms corresponding with respect to stacking boundaries, orientation of the pieces on the respective funicular surface, design iterations for the connections and finally structural analysis. Each iterative process will be covered in depth under its respective sub-heading further in the research paper.
A. Identify Materials

According to the statistics reported by the European Commission in 2011, soil and stones constitute 73% of the Construction and Demolition Waste. The highest amount of materials can be found in the horizontal layers i.e. floors and roofs rather than the columns and walls of typical buildings. The embodied carbon of buildings: typical floor and roof structures range around 440 kgCO2e/m². This is due to material extraction, manufacturing the market standard size tiles, transport to site, construction and demolition [24]. If these materials (e.g. Slate Stone widely used in the roofing industry) are reused instead of being recycled in the backfilling industry or creating slag for roads and pathways, the embodied carbon can be as low as 60 kgCO2e/m².

- Concrete, tiles, ceramics, insulation material - 26%
- Wood - 0.1%
- Metals - 0.002%
- Glass - 0.05%
- Soil and Stones - 73%
- Plastics - 0.01%
- Bricks, blocks, plaster - 0.2%

Therefore, in addition to the statistics provided above the material selected is slate stone for the following reasons:
1. Ease of availability - convenient to purchase off second-hand websites such as Leboncoin [20] and can be easily salvaged from construction sites.
2. Convenient to scan the standard sizes of stone available for reuse (approx. 600x900x3mm.)
3. Slate can be used directly without any transformation to the original shape thus bypassing energy for conversion.
4. Lastly, quality slate has a structural efficiency 3 times that of concrete [18] which makes it an ideal choice for building material of funicular forms.

B. 3D Scan

Initially the outlines of the pieces of slate were obtained by building dense point clouds using photogrammetry with an advanced image-based 3D modelling solution aimed for creating professional quality 3D content from still images. A 3D reconstruction using arbitrary images wherein photos can be taken from any position, provided that the object to be reconstructed is visible in at least two photos. But since this method resulted in a heavy and cumbersome model from the multitude of points obtained from all the pieces, it was much easier to just work with the boundaries and extrude the pieces post form finding.

This was done by capturing an image of all the pieces together with a ruler placed beside it in order to provide a reference with respect to the size and scale of the pieces. The images are then transformed from bitmaps into vector graphics using the Grasshopper Plugin – Trace [Section 8. Plugins Used (6)] (Fig. 2.B-1.) The pieces are then extruded with respect to their thicknesses thus, forming a digital library of the pieces of slate within a 3D modelling software wherein they can be stacked or aligned together to find best possible iterations on a 2D plane or can be made to orient on doubly curved surfaces making sure the planarity of the pieces is kept intact.
C. Stacking
Once the slate pieces are embedded in the 3D modelling interface they are run through a nesting script which in turn nests the pieces together within a pre-defined rectangular bounding region using the Grasshopper plugin Generation by Antonio Turiello. The spacing between the pieces can be edited by changing the nesting quality parameters which in turn ensures a tighter nest of the pieces within the bounding region. However, it is observed that this is not a very efficient method as the pieces do not rotate about their centers in order to ensure a tighter fit. Hence to make the process more intuitive the nesting algorithm is only used as an initial means for placement of the pieces together within a rectangular region. After which the pieces are run through a customized stacking script using particle spring systems. Individual pieces are stacked which each other through a sequence of three steps: Discontinuities along the periphery of the slate pieces are extracted along with the centers of the pieces. Lines are drawn within each piece by cross-referencing the extracted points from each piece. A high length factor is ascertained for these lines so as to ensure the slate pieces never lose their original shape when iteratively stacking together under a uniform force. (Fig. 2.C-0.)

Similarly, a Delaunay Triangulation is drawn through the already extracted centers of the individual pieces of stone ensuring all the pieces are connected within this network of lines as indicated in Fig. 2.C-1. A low length factor is assigned to these line segments since we want these lines to shorten once the simulation starts running in order to bring the pieces closer to one another negating the gaps in between pieces so as to form a dense stacking.

Lastly, a collision radius is assigned for all the pieces so as to deliberately leave a slight gap between the pieces to ensure they don’t overlap once they are oriented onto a funicular form. This step allows some room for play for the wood connections in between the pieces that would form a network, ultimately leading to a compression only structure.

For the purpose of iterative form finding several iterations of the stacking process on the XY plane were tested some of which are as follows:

1. **Stacking within a pre-defined boundary** so as to be able to test compression only arches. It works on the same principal as the original process with the only difference being that the pieces always align and stack with each other within a pre-defined boundary shape. As a result, a denser arrangement is observed as there is an additional strength factor of the boundary acting on the pieces forcing them to always stay within. Fig. 2.C-3.

2. **Introducing circular openings within the boundary**
   In this method the regions where the stacking is inconsistent resulting in large gaps between the pieces are assessed.

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Fig. 2.C-0. Reinforcing each piece to make sure it does not lose its initial shape under the force of the stacking process

Fig. 2.C-1. Triangulated movement of the slate pieces along their centers

Fig. 2.C-2. Stacking Process wherein slight gaps are left post simulation to ensure room for the wooden connections between the pieces

Fig. 2.C-3. Stacking within a pre-defined boundary
Larger shapes are introduced herein such that the pieces do not cross over into these shapes while stacking, thereby allowing the prospect of introducing openings of different shapes within the global geometry post form finding.

Fig. 2.C-4. Stacking around definite shapes

(3) **Double layer stacking** made possible on two identical boundaries that are offset from one another by a specific value in the z-direction. The two stacks are then superimposed on each other creating two layers of stacks which are then oriented on the funicular surface\(^4\) and an offset of it respectively, thus creating a double layer vault. It works on the same principle of the above stacking methods, but what this system does is it completely blocks out all the gaps between the pieces that are visible with a single layer stacking system. It is quite obvious this system is a much more complicated approach to solve but its advantages and perhaps a working solution is described further in detail towards the end of this paper as it serves a very promising domain (Fig. 4.0.).

Fig. 2.C-5. (a) Superimposition of the 2 layers (b) Double Layer Stacking

(4) **Overlap stacking** carried out again to address the gaps post form finding. Results from this stacking process are not very conclusive as it does not result in a uniform stack once oriented onto the funicular surface as observed in the last column in Fig. 2.D-0.

**Fig. 2.C-6. Overlap Stacking**

Shown below is an overview of all the stacking processes discussed above for comparison. (Fig. 2.C-7.)

Fig. 2.C-7. The different stacking iterations with the first one being the Original Option – Simple Stack described in the prototyping process herein

**D. Funicular Form Finding + Orientation**

Particle-spring systems [23] are commonly used to develop compression-only form-finding systems. This paper proposes to use a particle-spring system in response to a desired form obtained from a boundary surface post the stacking of pieces in order to generate a compression-only structure. Thus, the aim being to generate, build, and test a compression-only vault composed of slate pieces that are stacked together using the Simple Stack process seen in Fig. 2.C-2, and are oriented from the XY plane onto the funicular surface by tracing the centers of the pieces onto the surface and then aligning the two sets of planes and orienting the geometry using these planes onto the shell surface. The image below (Fig. 2.D-0.) shows the form finding using the boundaries derived from the 5 separate stacking processes seen in Fig. 2.C-7.

**Fig. 2.D-0. Funicular form finding with the different stacking processes**

Evidently, the remainder of the options do not give very consistent results as compared to the simple (0) and double layer stack (3) refer to Fig.2.D-0. For now, the paper

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\(^4\) Funicular Surface – They have only axial forces in either tension or compression for the loading case they have been designed for. Their shape is determined by the magnitude of horizontal thrust in it, which can be controlled in the force polygon, and the boundary condition.
focusses on a simple stack, addressing the advantages of the multi-layer stack later in the paper.

**E. Connections**

Once the pieces are oriented onto the vaulted surface their centers are obtained and a Delaunay Triangulation is carried out using these centers so as to define the axes of connections between pieces.

To further improve the rigidity of the structure the axes are subjected to another triangulation so as to ensure the pieces do not rotate about their axis under deformation and hence give stability to the structure.

The problem faced in the triangulation method is that the connections/joints are not in the same plane as the pieces. This is an obvious error as the end arms of the connection will never be in the same plane as the edges of two consecutive pieces hence making it impossible to attach the connections with the pieces. The problem is solved by extruding these lines in either direction thus forming a planar surface (Fig. 2.E-2.). The points resulting from the intersection events between the slate pieces and the extruded line surface can now be extracted which in turn gives us the start and end points of the connections between two adjacent pieces.

These points are used to generate one half of the arms of the connections. This geometry is then mirrored along the connecting lines between the pieces, thus forming a complete set of connections that hold the slate stone together. Their shapes are defined with respect to the thickness of the slate pieces attached to it.

Some Exploration of design ideas range from a CNC milled pipe connection to connections that can be 3d printed. But for the sake of ease of fabrication a more 2-dimensional approach is deemed feasible wherein both the arms of the connections are defined in a single plane (refer to Fig. 2.E-4.) so as to make them easy to manufacture.

The final arrangement of the connections with respect to the pieces wherein the change in angles at opposite ends of the connections are factored in by computing the average between the two end planes to define planar connections that can be easily fabricated by laser cutting. Due to the numerous angles created to ensure planarity of the slate pieces each connection is parametrically refined to fit its respective slate piece.
To counter the variation in thicknesses of slate stone, the connections designed for the 1:1 scale prototype are attached with adjustable arms (see Fig. 3.4.).

F. Structural Analysis

This research follows an important body of work from the past decade, which focuses on the design of global surface geometries for compression-only structural behavior (M. Rippmann et al. 2016) [3] (Brandon Clifford et al. 2015) [4]. For example, studies in thrust network analysis have made possible the design and computation of complex unreinforced freeform shell structures that work purely under compressive forces once they are completely assembled (Block, 2009) [11]. The structural analysis includes a global analysis that evaluates the equilibrium of the structure in its final state. The analyses are conducted with Karamba, a finite element analysis plug-in for Grasshopper (Preisinger, 2013), and directly contribute to the design and distribution of the wood connections by coordinating different type of constraints: structural (type, direction and magnitude of reaction forces). Specifically, the analyses consider reactions generated at boundary conditions between elements and at the interface with the ground to determine the types and locations of necessary details.

A structural analysis under a load of approximately 4.5 kN/m² results in a buckling factor > 5. The load cases are defined by a combination of wind load (15kg/m²) and the self-weight (30kg/m²) of the structure. The connections are defined as lines and input into the line to beam command and characterized as box sections for the purpose of structural evaluation and in order to ascertain their ideal depth to be able to withstand the above-mentioned loads. The majority of red areas seen in the image reinstate the fact that the plates are in compression and due to the geometry of the connections the structure is stable because of its self-weight. Moreover, Slate has a Young's Modulus ranging from 10-100 MPa (Mega Pascals) thus good quality slate has 3 times better structural efficiency as compared to concrete - this can be attributed to the fact that used slate has undergone weathering process over the years which results in it breaking away parts of lesser structural integrity therefore the stone that is salvaged is very durable and perfectly suited for the form finding process described in this paper. Furthermore, since it is a vaulted structure it is highly efficient due to the use of axial loads instead of bending loads.

III. ASSEMBLY

Two prototypes were assembled for the sake of this research. The first model (Fig.3.0.) was built using actual pieces of slate stone that are scanned using the workflow above and input into the digital modelling interface. The connections are tagged and baked in rhino after which they are laser cut. As visible the connections are not very rigid and glue has to be applied in order to hold the pieces together. This is due to the fact that the exact locations where the connections fit onto the pieces are not marked and the variable thicknesses of the stone pieces are not

5 Young's modulus is a mechanical property that measures the stiffness of a solid material. It defines the relationship between stress and strain in a material in the linear elasticity regime of a uniaxial deformation

SI unit: pascal
considered resulting in a poor interpretation of the final digital design.

Fig. 3.0. First cut prototype and future triangulated connection assembly

The second prototype is carried out on a 1:100 scale so as to assess through a live model the behavior of the connections with respect to the pieces. The assembly process requires an efficient naming and tagging system of all the pieces as well as the connections in order to be able to build it with ease and follow a specific order so as to negate or minimize the use of falsework in order to support the pieces during construction. The slate pieces are first numbered and assigned a tag at all the points on the edges of each stone, these are the precise positions where the connections will be fastened in order to connect the adjacent pieces. All the connections are then numbered from first to last and similarly assigned a tag at the end of each arm corresponding to the number of the slate piece they are going to connect to. Consequently, as mentioned above a similar tag denoting the main identifying number of the connection is assigned on the edge of their respective slate pieces. The anchor pieces at the base are similarly numbered and tagged. Once the tagging process is complete all the pieces are oriented onto the XY plane on the Rhino canvas in three separate groups namely the slate pieces, the connections and the base pieces. These items are then baked into the rhino interface from grasshopper and finally cut using a laser-cutting machine. The cut pieces are then laid out in chronological order in their respective groups.

The assembly is carried out starting from the topmost piece and slowly worked downwards towards the base. This ensures that there is no use of supports or falsework in order to hold the pieces at the top in their place as they are consequently always being supported by the lower ring of connections and being lifted higher as the assembly is carried out.

Fig. 3.2. Assembly order

Once the entire model is assembled including the horizontal base pieces, it is attached onto pre-defined grooves onto a base plate. These grooves match the exact boundary periphery conditions as defined in the digital model. Thus, in order to snugly fit into the grooves all, the connections and pieces have to be fit precisely in their denoted positions thereby maintaining the exact design shape and ensuring the global geometry is always in compression.

(a)

(b)
A 1:1 scale wood connection shows the adjustable arms that incorporate the various thicknesses of the salvaged slate stone. The arms can be adjusted along their vertical axes perpendicular to the direction of the arm by means of a screw that can be forced inwards or outwards depending on the thickness of the slate stone.

The following inferences are derived from the computational workflow and fabrication of the prototype described in the research paper:

- Planarity of pieces is maintained due to the excellent behaviour of slate stone under compression coupled with the wood connections.
- A well defined and systematic numbering/tagging system ensures the prototype is very easy to assemble even though it has a complicated form and connection arrangement.
- A top to bottom assembly of the prototype is favoured due to ease of fixing the connections with the pieces.
- The wood connections can be easily milled or laser cut, excellent properties of wood under compression and tension.
- The adjustable connection arms factor for the varying thicknesses or broken edges of the slate stone and fit precisely. Hence, avoiding the use of glue as compared with the first prototype.
- The connection axes are triangulated a second time (see Fig. 2.E.1.) in order to form a more rigid assembly system.
- The structure can withstand heavy loads as observed with the placement of a book on the vault.
- The arrangement of the connections for the prototype is designed such that it is easy to attach multiple layers of stone assemblies offset from the original one in order to replicate the multiple layer stacking systems (see Fig. 4.0.).
- With so much attention being paid to slate stone being the primary reused material, it is interesting to point out that most of the wooden connections have been fabricated from salvaged wood planks from the lab the prototype was being fabricated in.

V. ADDITIONAL TESTS

A. Multi-Layer System

If we look towards nature for the most commonly occurring stacking processes, a prime example is the cross section of a pearl. When observed under an electron microscope it reveals a complex network of multilayer stacking. What this does is it not only gives high rigidity but also an ability to span surfaces with double curvature at the same time making it very resilient.

Based on these observations a double layer stacking was carried out within a predefined boundary. The only difference being that instead of defining wood connections...
between adjacent pieces, here two pieces are glued together with a wood spacer between them such that the distance between the pieces is slightly greater than the thickness of the pieces. Each double layer joint is then slid into the gap of the next one thus forming a 4-layer system. It works on the principal of one joint supporting two other joints and being supported by two separate joints. It's easy to form global curved surfaces with this form of stacking with the only drawback being that the stone pieces are subject to shear loads which might result in the pieces giving way.

Another test was carried out wherein a chitosan mix was poured over a simple stack and then allowed to dry for 24 hours (Bornaz, 2018) [28]. This allows the stack to retain its original shape but lends it an additional layer of flexible chitosan which not only fills up the gaps between the pieces, but also lends the whole stack with a malleability of fabric as a result allowing it to take the form of complex curved shapes just like a piece of cloth, but with an added stiffness to be able to hold its shape once defined. Reinforcing the idea that it could serve as a secondary skin in roof or facade design.

VI. CONCLUSION + WAY FORWARD

The research applications successfully show the marriage of two salvaged materials to give rise to a complex form. This is achieved by understanding the respective inherent material properties of both the elements. Consequently, linking the two such that they give rise to a unique synthesis in terms of design and structure. Reinforcing the fragility of slate stone using rigid wood connections as illustrated in the compression only prototype provides an interesting premise for future research. Furthermore, the system is designed keeping in mind future disassembly so that these materials can be reintroduced into the product lifecycle chain. The prototype inspired by the multi-layer stacking system takes inspiration from and highlights the inherent stacking within a range of biological forms all around us and mimics these naturally occurring phenomenon. Though, it does not prove very successful with slate stone but applications of these ideas with denser and stronger materials could prove very fascinating indeed. Similarly, applications with bioplastics such as chitosan replacing the wood connections offers an entirely new premise to work with. During the course of prototyping it was deduced that if slate stone is replaced with a material that behaves well under tension, applications of this workflow can be carried out on a wider range of possibilities such as facades of buildings, and anticlastic surfaces wherein the connections can be aligned on asymptotic, geodesic or principal curvature lines. (see Fig. 6.0.).
To summarize, this research successfully demonstrates a new method to design, analyze and construct complex geometry shell structures which address a myriad of architectural concerns, without the need for extensive formwork or templating. Through computation, digital fabrication and the adaptation of detailing strategies, this method points to a possible application of design in synchronous feedback with the constraints of assembly. While the potentials of such a method accommodate an endless number of possible geometries, the analysis points to a series of constraints. These constraints exist primarily in the structural and material properties of the salvaged stone pieces and the wood connections, the geometric constraints of fabrication and the problematics of compounding errors during assembly. Future research seeks to further evaluate the capabilities of assembly simulation and sequential fixing in the construction of full-scale structures constructed entirely out of salvaged materials.

VII. PLUG-INS USED

1) Kangaroo Physics (Daniel Piker) - Kangaroo is a Live Physics engine for interactive simulation, optimization and form-finding directly within Grasshopper.

2) Karamba (Clemens Preisinger in cooperation with Bollinger-Grohmann-Schneider ZT GmbH Vienna) - Karamba is a parametric structural engineering tool which provides accurate analysis of spatial trusses, frames and shells. Karamba is fully embedded in the parametric design environment of Grasshopper, a plug-in for the 3d modeling tool Rhinoceros. This makes it easy to combine parameterized geometric models, finite element calculations and optimization algorithms like Galapagos.

3) RhinoVault (Dr. Matthias Rippmann Dr. Lorenz Lachauer Prof. Dr. Philippe Block) - The Rhinoceros® Plug-In Rhino-VAULT emerged from research on structural form finding using the Thrust Network Analysis (TNA) approach to intuitively create and explore compression-only structures.

4) WeaverBird (Giulio Piacentino) - Weaverbird brings mesh editing, subdivision and mesh transformations to Rhino and Grasshopper users.


6) Trace (Gerard) - Transforms bitmaps into vector graphics.

7) Anemone (Mateusz Zwierzycki) - plug-in which enables you to create loops in Grasshopper.

8) Galapagos (David Rutten) - Evolutionary computing for Grasshopper.

9) WombatGH (Andrew Heumann and Brian Ringley) - a series of miscellaneous utilities aimed at improving modeling processes by streamlining common tasks. It includes components for operating on geometry, lists, files and folders, and visualizing the geometric properties of surfaces and meshes.

10) Generation (Antonio Turiello) - Provides additional components to explore, animate and fabricate generative shapes with Grasshopper

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