An integrated form-finding and automated fabrication approach for exploring sustainable shell structures

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Abstract. Latest advances in computational design and automated fabrication provide opportunities for form-finding and precise development of shell structures in an integrated design to fabrication context. Implementation of these techniques cannot be completed without considering the negative effect of construction in the environment and the urgent need for environmental impact reduction through reusability and recyclability. This paper deepens into this direction by presenting a form-finding/automated fabrication approach of shell forms in combination with a recycle material implementation. The process starts by examining form-finding possibilities of funicular forms by producing a series of case studies based on a number of controlled parameters, physical attributes and static performance criteria. Then, an alternative use of construction materials is presented, in order to achieve sustainable properties, and adequate static performance of both, the overall structure and the individual structural components. In order to achieve this, cylindrical samples of different recycle material combinations are produced, tested under compression and their implementation is discussed. The suggested integrated form-finding to automated fabrication approach offers the opportunity for a holistic sustainable approach towards shell structures development, aiming at shape and performance viability through the selection of recycle materials.

Keywords. Shell structures, Thrust Network Analysis, computational design, flexible formwork, wasted materials, sustainable construction.

1. Introduction
The description of mathematical forms of arches, but also their mechanical properties that have been studied in the 17th century with the prominent work by Robert Hooke on compression-only structures [1], has inspired architects and engineers in finding new ways and techniques to give form to arches, domes and shell structures [2]. These techniques are still a source of inspiration and are used as precedents for architects and engineers until today. Currently, various techniques attempt to simulate the form-finding process and at the same time provide three-dimensional equilibrium; generating compression-only vaulted surfaces and networks [3]. Same as with the methods of form-finding, the current advancement of technology in automated fabrication allows for more flexibility in the construction process. The matrix, processing or manufacturing of new and/or existing materials is also evolving, with an urgent need to turn towards more green and circular approaches.
Prominent examples towards integrated form-finding and automated fabrication, attempting to eliminate the environmental impact of materials and structures can be found in the work by Block Research Group [4]. In these examples Thrust Network Analysis [3] is used to generate forms of different shell structures in combination with advanced fabrication and assembly techniques. Among others, their projects include the Free-Form Tile Vault, which implemented advanced digital fabrication in combination with traditional timbrel or Catalan tile-vaulting techniques but also applied recyclable and reusable cardboard falsework for assembly, reducing dramatically the material and labour cost [5]. Also, the Nest HiLo Shell Roof project implemented a lightweight and flexible formwork consisting of a net of tensioned cable and a tailored fabric that was then sprayed with a textile reinforced thin concrete in order to reduce material waste [6]. Moreover, the project Knitcandela, which introduced an ultra-lightweight knitted formwork with pockets filled with balloons and then sprayed with a thin layer of concrete, provided a structurally efficient waffle shell without any additional complex and wasteful formwork [7]. Finally, the Armadillo Vault project, a thin shell structure that was fabricated without any reinforcement provided an example where complex and free-form geometries can be developed with an efficient and effective use of material, both in the case of temporary falsework and stone voussoirs [8].

The above examples, but also other current and advanced ones, consider the detrimental impact on the environment by the construction sector, knowing that it is responsible for over 40% of the world’s energy usage, it produces 50% of the world’s landfill waste, it creates 23% of the world’s air pollution, 40% of the world’s drinking water pollution and it causes 50% of climate change [9]. Indicatively, it can be mentioned that 2.01 m³ billion tons of municipal solid waste are generated every year by cities worldwide with an expected grow to 3.40 billion tons by 2050 [10]. Hence, recently the construction sector is opting to incorporate sustainable initiatives in this direction, considering waste materials as the driving force and part of an up-cycling process, which can minimize new inputs and exhaustion of natural resources and maximize recycling [11]. Among others, these include energy efficient and materials certificate systems [12], like Green Building, which uses environmentally friendly materials and methods during the construction process in an attempt to save 250 metric tons of CO₂ emissions annually [9]. Also, terms like ‘urban mining’ are implemented, in order to reclaim materials from solid waste materials or undesired products, mostly valuable metals or rare earths, that now occur more in man-made dumps in the built environment [13].

As it has been mentioned, waste materials can be part of the up-cycling process by their mixing, attempting to create new ones with superior properties in terms of environmental impact reduction and at the same time to persist their structural and construction performance. These combined new materials might even have higher performance in quality, material properties, financial or environmental value than the individual components before being combined, but they can also be reused or recycled. Currently, a wide range of waste/recycled materials that are repurposed in the production and more specifically in the construction process have been found.

Among others, examples include recycled materials made from paper and cardboard wastes, Polyethylene Terephthalate (PET) and TetraPak wastes [13]. All categories have been implemented in the construction of buildings and structures with respective advantages to be found in each one. Projects like NewspaperWood, PHZ2 and Paper Tile Vault [4] implemented recycle paper and cardboard in different shapes and procedures due to their ability be easily manufactured but also their compressive strength, lightweight properties, sound and thermal insulation qualities. Projects like Plasphalt utilized plastic waste as an alternative to mineral aggregates such as sand and gravel in asphalt cement for applications in road surfaces, achieving durability on the one hand and reduction of cement by 7% on the other hand. Finally, project like Turff Roof utilized TetraPak, a material made from paper, polyethylene and aluminium, in order to produce waterproofing sheets with fireproof, flexible and corrosion free properties but also with high reflectance to heat radiation [13].

Current work considers both, the application of advanced computational tools and fabrication technologies in the development of compression-only structures, and at the same time, emphasis is given on the use of recycle materials. Ultimate goal is to deepen into the importance and urgent need for integrated approaches that can contribute towards a more environmental conscious construction sector,
and at the same time can keep design and structural adequacy with special attention to shell structures. The suggested framework of development from design to fabrication is considered as the basis for further structural development towards sustainable construction. As a result, this work can be part of an open-ended development process whereas several iterative feedback loops can be included from the last fabrication to the initial design stage. In the following section related methodological steps are presented for the development of sustainable shell structures. The geometrical exploration of shell forms is presented based on three case studies and related aspects of automated fabrication are discussed. Furthermore, recycle material properties based on compression testing results of different samples is discussed.

2. Methodological steps

The current work implements Thrust Network Analysis for funicular shell structures generation as the preliminary geometrical investigation step, which leads to the production of a series of case studies that are examined in terms of their automated fabrication possibilities based on different recycle materials. Three basic methodological steps are introduced in the process of sustainable shell structures development: Thrust Network Analysis and geometrical investigation, automated fabrication and recycle material selection.

2.1. Thrust Network Analysis and geometrical investigation

Thrust Network Analysis is a methodology for three-dimensional equilibrium, generating compression-only vaulted surfaces and networks. It was inspired by O’ Dwyer’s work on funicular analysis of vaulted masonry structures [14] and extended by Block Research Group by adding the concept of duality between geometry and in-plane internal forces of networks [4].

Currently, parametric design software, particularly plug-ins based on Thrust Network Analysis, for instance rhinoVAULT [15] (plug-in for Rhino [16]), enable form-finding of compression only structures and funicular forms by adopting the same advantages of Graphic Statics [17]. The use of reciprocal diagrams provides an intuitive and fast method for generating three-dimensional forms and at the same time, the opportunity for users understanding of the underlying structural principles. The specific plug-in incorporates a series of commands in associative steps that are used to generate shell structures and funicular forms with certain diagrams via control parameters that among others include the shape of the structure in plan-view, the boundaries, the openings, etc.

More specifically, rhinoVAULT generates a funicular shell form, the Thrust Network G, but also generates two more diagrams; the form diagram \( F \), which is the shell in planar projection, as well as the reciprocal force diagram \( F^* \) to determine equilibrium, which can present three-dimensional loads in a two-dimensional manner. The current work applies rhinoVAULT plug-in for the geometrical generation of a series of case studies that can be qualitatively evaluated and discussed in terms of their effectiveness to be used throughout the next two steps.

2.2. Automated fabrication

The step of automated fabrication process consists of two parts. The first part deals with the subdivision of the shell surfaces, the creation of 3D components, their individual identification and collection of their geometrical data. The second part consists of the separation of the components and the design of a flexible pin-bed system for the automated fabrication of each structural component. The suggested flexible pin-bed system is capable of adapting to different sizes, forms and angles of all components comprising the overall shell form. Both parts are explicitly simulated in the parametric environment of Grasshopper plug-in [18] (plug-in for Rhino), in order to evaluate the feasibility of the suggested automated fabrication process.

2.3. Recycle material selection

With regard to the material selection step, cement is the matrix material used together with recycle material additives that specifically include textile fibers, tetrapak stripes and polystyrene. Several
different combinations are used, leading to a series of samples that are mechanically tested. The test results, as well as comparisons of the samples on a number of different factors provide the materiality of the shell components.

3. **Results**

3.1. **Geometrical exploration of shell forms: Case studies**

This section demonstrates the geometrical development of case studies based on Thrust Network Analysis using the rhinoVAULT plug-in. All forms start off as a 10x10 m square surface that is then modified as to give a range of different results. The modifications and the controlled parameters of all options include; the number of sides raised above or touching the ground, the number of convex or concave edges and the level of curvature of such edges, resulting to differentiations in their shapes. The parameters used to compare their physical properties include; height of shells, height of openings if any, area below shells, surface area of structure and area of habitable space. Specifically, three distinct categories of case studies, A, B, and C are examined (Figure 1).

![Case A, Case B, Case C](image)

**Figure 1.** Representative results of the 3 categories of case studies generation.

3.1.1. **Case studies A.** In this case the exploration and respective results refer to shells without openings or raised edges. In order to achieve compression-only results, the edges of these 4-sided shells need to be either straight or concave. Within this framework, different levels of curvatures are examined in order to perceive differentiation in terms of their physical properties as well as their static performance (Figure 1a).

3.1.2. **Case studies B.** In this category of case studies exploration, geometrical parameters of shells involve two parallel openings formulating a funicular structure with two raised edges and two edges touching the ground. In this case, in order to achieve compression-only results, the raised sides cannot be convex or straight, but can only be concave. Differentiation of their geometry is associated with the level of curvature of the raised edges, as well as the form of the non-raised ones; linear, concave or convex (Figure 1b).

3.1.3. **Case studies C.** In this case, exploring options of shells refer to four openings; all edges are raised and only the 4 corners are touching the ground (Figure 1c). Respective open shells can be in compression only if the sides are concave and not straight or convex. Differentiation of their geometry by varying the level of curvature can be achieved.
Figure 2. High performance case studies B02, B05 and C02. Images indicate: 1. Thrust Network, 2. Form diagram, 3. Force diagram, 4. Shell form indicating the largest (red) and smallest (blue) components.

After analyzing all case studies, results are derived in terms of the highest performing shell structures based on their physical attributes but also their static performance based on Force Diagrams. Specifically, the selection initially refers to three case studies with the best performing results to be followed by the selection of one case study that can be further processed in automated fabrication step.

Figure 2 demonstrates the best performing case studies B02, B05 and C02, which are evaluated with regard to their highest physical attributes (Habitable/Total Area and Shell Surface Area) and their lowest load of forces spread across their edges (Force Diagram).

Following the selection of the 3 case studies based on physical attributes and static performance, the final single choice involves additional criteria related to automated fabrication. Within this framework, case study B02 is selected for demonstrating automated fabrication due to the uniformity of its individual components and their less complicated process of assembling.

3.2. Automated fabrication

3.2.1. Discretization of structural components. After the selection of best performing case study B02, the process continues by discretising the shell structure in order to identify individual structural components. Briefly, the algorithm produces a surface following the initial shell form and then is subdivided in an X number of components, which can be parametrically controlled in terms of their number and thickness. Lastly, the individual components as twisted boxes are identified, numbered and their geometric data are listed, in order to allow their comparison (smallest and largest components).

3.2.2. Analysis of individual components. Four types of components are selected from case study B02 for the comparative analysis of their geometrical properties, which guides the flexible formwork design (Figure 3). The first type consists of components no. 91, 103, 121 and 133, which are symmetric in pairs, with a volume of 0.060 m$^3$ and differentiated edges lengths. The second type consists of components no. 01, 13, 211, 223, again symmetric in pairs, with a volume of 0.053 m$^3$ and differentiated edges lengths. The third type is represented by component no. 112, with a volume of 0.073 m$^3$ and differentiated edges length. The fourth type includes components no. 32, 42, 182, 192 that are symmetric in pairs, with a volume of 0.049 m$^3$ and differentiated edges length.
3.2.3. Flexible formwork design and adaptation. In the next step of the process, the selected individual components are used as the starting point for the design of flexible formwork. Initially, the individual components are positioned on a given XY surface. Then, pins are designed and raised below their surface to a necessary height in order to reach their bottom surface and essentially create a pin-bed system. The vertical edges of the components are trimmed so that they are perpendicular to the XY plane, allowing fabrication performance of all components of the entire structure by a single flexible formwork. In addition, the specific design is capable of taking any of the above shapes with different lengths of sides but also with different sizes of angles at the corners. The selected automated fabrication allows reduction of formwork material waste and cost and hence promotes higher sustainability rates in comparison to conventional fabrication approaches [19].

Figure 4 demonstrates an exploded axonometric of the suggested flexible formwork. It consists of two parts, each one is flexible and responsible for different physical fabrication operations. The first part deals with the adaptation of shape on the XY plane. In order to achieve this, four vertical planks that are flexible in orientation and position are used, which determine the size and shape of individual components. The second bottom part consists of a planar bed with rising vertical pins, which are responsible for forming the curvature of the bottom twisted surface of each structural component. Figure 5 represents two adaptive possibilities of the flexible formwork by varying the size, the angles and the length of the vertical sides as well as the curvature of the bottom surface.
3.2.4. Joints and assembly of structural components. Different commonly used methods of assembling shell structures can be found, which have been applied in several projects such as the Paper Tile Vault and the Free-form Tile Vault. In the first case, a framework structure was developed that was temporary supported in order to position the units [13]. In the second case, no external supports were added to the brick structure but a temporary falsework was created for the assembly process made of recyclable and reusable cardboard [5]. In the current work, all individual structural components produced by the flexible formwork are interconnected by applying a joint on each vertical side that achieve the connection of shell according to adjacent unit components (Figure 6).
A possible assembly process includes the connection of units in each row or arch between them, their positioning on site using a temporary support, and then, the connection of the next interconnected row or arch of structural components onto the previous one until the overall structure is assembled. Once all rows/arches are connected, the temporary support can be safely removed, to reveal a free-standing, compression-only shell structure. This method could also allow the structure to be disassembled, stored or shipped to a different location to be re-assembled in an easy and effective way, offering superior sustainable advantages compared to conventional approaches.

3.3. Recycle material selection and compression tests
Apart from the already introduced flexible formwork as a sustainable alternative fabrication process, material selection is also an important part of the process. In order to increase the sustainable potential of the suggested approach, a selection of recycle material additives that is followed by their mechanical tests is demonstrated in this subsection. Within this framework, cement is chosen as the matrix material due to its binding properties; when mixed with water it has the ability to set, harden and adhere to other materials, binding them together, and remains in its hardened state once reached. The recycle additives used in the samples are textile scraps, TetraPak strips and polystyrene (Figure 7).

Textile scraps are made of fibres that can be used as reinforcement and controller of cracking. The fibre bundles can be arranged in the direction of the main tensile stresses, making them more effective than short-cut fibres [20]. Using them as an additive to a composite material also gives them a repurpose as they usually end up in waste from factories, cloth makers, fashion schools, etc. TetraPak consists of three different components carrying different properties; cardboard, aluminium foil and a plastic membrane. Containers made of TetraPak are often disposable or need a special process for its components to be separated before they can be recycled [21]. The different properties offered by each of them, could benefit the final composite material. Polystyrene generally has short-term use and it is a plastic that is not commonly recycled as expanded polystyrene should not go into the recycling [22],

![Figure 6. Connection detail between components.](image)

![Figure 7. Additive materials used: Textile scraps, TetraPak and polystyrene.](image)
therefore repurposing it would be a sustainable solution. It is very lightweight and when used as an additive to cement or any other matrix material, it could lower the total weight as well as decrease the volume of other materials used.

A number of samples are physically produced, initially to test their mechanical performance under compression. Wasted textile scraps were collected from local textile stores as well as a fashion studio, were cut and torn into different sizes. TetraPak cartons were collected after having been used and were then cut down into thin strips of different lengths. Used polystyrene as protection in product packaging was collected and broken down into smaller pieces and if possible down to individual bubbles. Specifically, nine different mixtures were prepared for the compression test, with the following material and proportions used as the main components; 1. Cement (1), 2. Cement (1) + Polystyrene (1), 3. Cement (1) + Polystyrene (1.7), 4. Cement (1) + textile scraps (1.5), 5. Cement (1) + textile scraps (1) and Tetrapak strips (1), 6. Cement (1) + Tetrapak strips (1.5), 7. Cement (1) + Polystyrene (1) + textile scraps (1) + Tetrapak strips (1), 8. Cement (1) + Polystyrene (1) + textile scraps (1), and 9. Cement (1) + Polystyrene (1.5) + textile scraps (1.5).

Samples were produced by using a plastic cylinder mould with dimensions of diameter 10 cm and height 15 cm. The nine sample mixtures were poured into the cylinder moulds, levelled at the top and left to set for 24 hours. Once set enough to be removed from their flat base, they were placed in a container filled with water. Two days later, they were remoulded and placed back underwater to soak for at least a week before being ready to undergo the compression test (Figure 8).

![Figure 8. Nine different mixtures for compression test.](image_url)

All samples were measured for an accurate calculation of volume and $\lambda = 1/d$. They were also weighed on an accurate table top scale, as well as when submerged in water, by hanging from the scale with a string for an accurate calculation of their density. Once all data was collected, each of the samples were tested on a compression machine. Figure 9 demonstrates the compression test results, which clearly indicate that Sample no.1, i.e. the one consisting of only cement, has the best performance. This means that any of the additive material selected makes the mixture weaker in compression, unlike in tension. Nevertheless, considering that the minimum average compressive strength of bricks is normally 7.5 N/mm², all samples besides Sample no.3 reach and exceed this value.

Sample no.3, made of cement (1) and polystyrene (1.7), has generally low performing results as the amount of the latter added reduces its density, making it much weaker under compression. This indicates how the quantities should be controlled and tested, when polystyrene is used as an additive to make a mixture more lightweight and to reduce the amount of any matrix material used, in this case cement. Regardless of Sample no.1 having the best overall test results, other mixtures can also be considered when bearing in mind the minimum average compressive strength as well as the fact that other parameters also play an important role in the choice of materials in the construction of shell structures, for example being lightweight.

Out of the remaining seven samples, Sample no.5 has the best performance. It is made out of cement (1), textile scraps (1) and TetraPak strips (1). Sample no.6 is made of cement (1) and TetraPak (1.5), and Sample no.4 follows, that is made of cement (1) and textile strips (1). The next best results are obtained with Sample no.7, which is made of cement (1) and all three additives combined (1). Textile scraps and TetraPak strips control its strength; as indicated when compared to Sample no.2 that has the same amount of polystyrene, but lower performing results under compression. It is observed that when the mixture consists of a combination of the other two additives, the results are better. Adding
polystyrene to a mixture can make it less dense and more lightweight and when its quantity is controlled and kept to a certain minimum, then the mixture does not lose much of its strength or its ability to be used in construction. When comparing the results of Samples no. 8 and no. 9, it can be observed that large quantities of additives can greatly reduce the mixture’s strength. When controlled and combined with other materials though, the mixtures strength can remain in a well-performing and safe range.

![Figure 9](image.png)

Figure 9. Charts indicating the compression test results.

It has been generally observed that cement’s strength is reduced when combined with external materials, however, samples produced by those mixtures do not exit the required compressive strength level. Other important advantage is the reduction of the amount of cement used through sustainable and repurposed materials, which makes the structures more lightweight and adds aesthetic value to the appearance of the blocks. Other materials can be therefore incorporated but their quantities need to be tested and controlled. Polystyrene can reduce the amount of cement used and Tetrapak and textile scraps can regain the lost compressive strength caused by the incorporation of polystyrene bubbles. All of the additive materials can add aesthetic value to the structure and can be placed in the mould in such a way to be visible and reveal the shell’s materiality to the public. The shells can be used for a range of activities. They can be assembled and disassembled and moved to a different location and start their cycle all over again.

4. Conclusion

In conclusion, the suggested integrated form-finding to automated fabrication approach offers the opportunity for a holistic investigation of issues that concern the design and construction industry nowadays. The effort to explore construction systems that begins with the form-finding process using advanced computing techniques for shape and performance viability and ends with the physical production of entire structures ready for use needs to be indispensably associated with techniques of recyclability and reusability as a new endeavor in fabrication approaches. This, might offer a sustainable alternative approach to the existing conventional and less viable techniques in construction industry. Furthermore, the suggested framework could support an open-ended process with back-and-forth steps, enabling iterative feedback loops from the last stage to the initial early design stage of the process.
References
[1] Block P, Dejong M and Ochsendorf J 2006 As hangs the flexible line: Equilibrium of masonry arches vol 8
[2] Adriaenssens S, Block P, Veenendaal D and Williams C 2014 Shell structures for architecture: Form finding and optimization vol 9781315849 (Routledge)
[3] Block P 2009 Thrust Network Analysis: Exploring Three-dimensional Equilibrium (Massachusetts Institute of Technology)
[4] Block Research Group 2019 Block Research Group Block Res. Gr.
[5] Loápez Loápez D, Van Mele T and Block P 2016 La bóveda tabicada en el siglo XXI Inf. la Constr. 68
[6] Méndez Echenagucia T, Pigram D, Liew A, Van Mele T and Block P 2019 A Cable-Net and Fabric Formwork System for the Construction of Concrete Shells: Design, Fabrication and Construction of a Full Scale Prototype Structures 18 72–82
[7] Popescu M, Rippmann M, Liew A, Reiter L, Flatt R J, Van Mele T and Block P 2021 Structural design, digital fabrication and construction of the cable-net and knitted formwork of the KnitCandela concrete shell Structures 31 1287–99
[8] Rippmann M, Mele T Van, Popescu M, Augustynowicz E, Echenagucia T M, Barentin C C, Frick U and Block P 2016 The Armadillo Vault: Computational Design and Digital Fabrication of a Adv. Archit. Geom. 2016 344–63
[9] Sikra S How Does Construction Impact the Environment? | GoContractor
[10] Kaza S, Yao L C, Bhada-Tata P and Van Woerden F 2018 What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050 (Washington, DC: World Bank)
[11] Lucertini G and Musco F 2020 Circular Urban Metabolism Framework One Earth 2 138–42
[12] Haselsteiner E, Rizvanolli B V, Villoria Sáez P and Kontovourkis O 2021 Drivers and barriers leading to a successful paradigm shift toward regenerative neighborhoods Sustain. 13 5179
[13] Hebel D E, Wisniewska M H and Heisel F 2015 Building from Waste : Recovered Materials in Architecture and Construction.
[14] O’Dwyer D 1999 Funicular analysis of masonry vaults Comput. Struct. 73 187–97
[15] Rippmann M, Lachauer L and Block P 2012 Interactive vault design Int. J. Sp. Struct. 27 219–30
[16] McNeel 2021 Rhino - Rhinoceros 3D
[17] Akbarzadeh M and Hablicsek M 2021 Algebraic 3D Graphic Statics: Constrained Areas CAD Comput. Aided Des. 141 103068
[18] Davidson S 2015 Grasshopper Algorithmic Modeling for Rhino Add-ons Grasshopp.
[19] Kontovourkis O and Konatzii P 2021 Environmental and cost assessment of customized modular wall components production based on an adaptive formwork casting mechanism: An experimental study J. Clean. Prod. 286 125380
[20] American Concrete Institute Textile-Reinforced Concrete Topic
[21] Miles L Why Tetra Paks aren’t Green or Sustainable | Treading My Own Path | Zero Waste + Plastic-Free Living
[22] Recyclenow Polystyrene packaging | Recycle Now