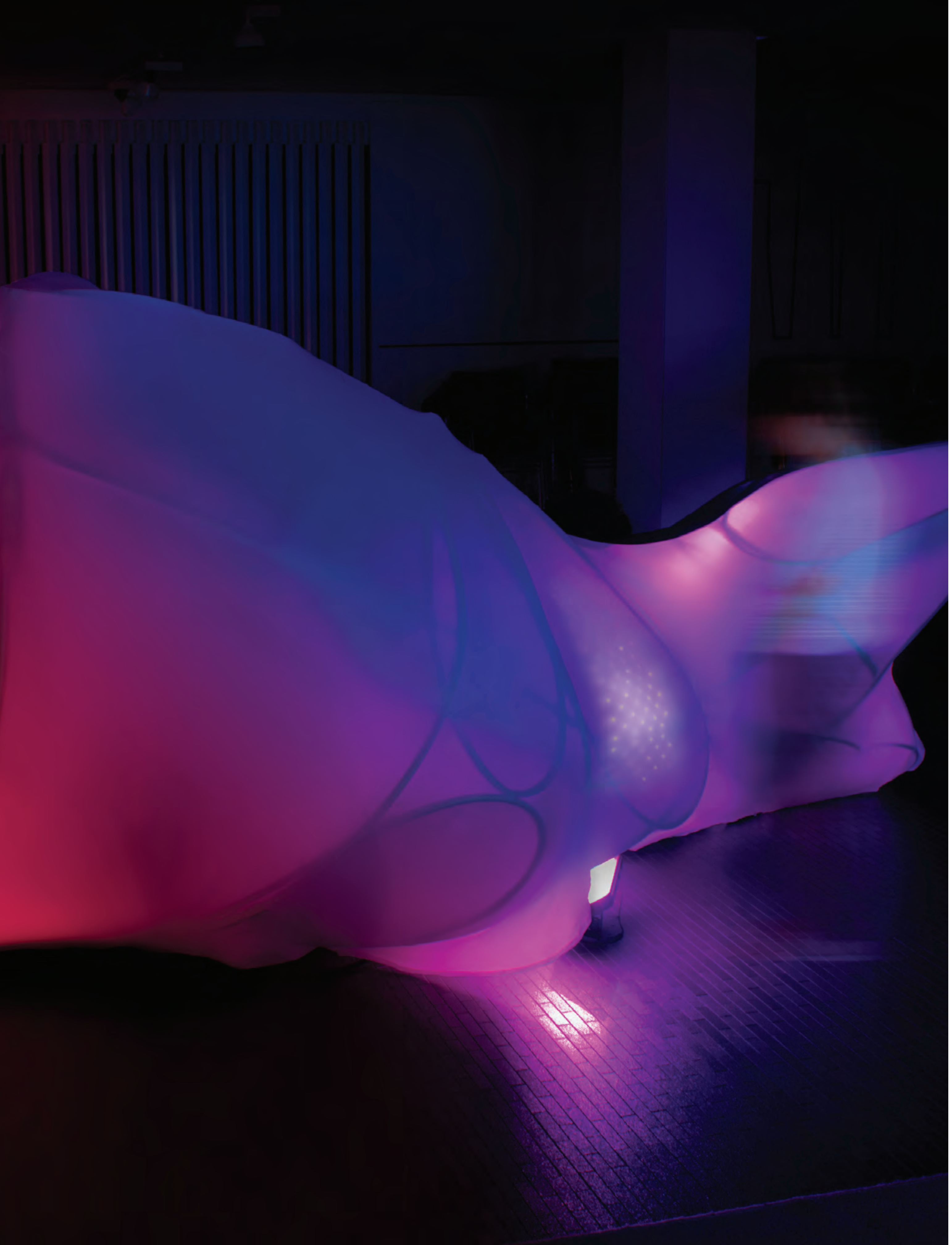

Flexible Discreteness: Computational Design Methods for Flexible Linear Elements

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1 INTRODUCTION

Although CAD tools were early adopted in architecture as drafting tools, it was not until the late 90s/early 2000s when the use of "digital tools" started to become inherit to architecture. NURB surfaces widely present in the so-called "digital architecture" allowed for a mathematical description of a space. This leads to a "more fluid logic of connectivity," as Greg Lynn describes in "architectural curvilinearity" (1993).

The premise of the continuous space has been materialized during the last decades by architects such as Zaha Hadid or Coop Himmelb(l)au. However, in order to fabricate the complex structures generated in a digital environment, a post-rationalization process is required. This leads to the discretization of these surfaces into panels, slices, or waffles.

The research presented in this paper focuses primarily on the use of flexible elements as discrete units, as opposed to the NURB surfaces widely present in the so-called "digital architecture" of the 90s and 2000s. It aims to create an architecture configured as an aggregation of discrete flexible lines, rather than as a continuous surface which requires post-rationalization to be materialized.

An open-source software "Softmodelling" (fig. 1) was created in order to gain control over flexible architectural elements, enabling their assembly into highly complex and heterogeneous structures. The flexible nature of those elements facilitates the local variation in the stiffness across the structure. Simple modeling operations allow the control of their distribution, connectivity, and deformation, while also facilitating a digital manufacturing workflow for their assembly.

The research argues that the establishment of such a workflow will increase efficiency and speed in the production of flexible structures, as well as enable complex material organizations.

2 DIGITAL FORM-FINDING

Contemporary advanced simulation programs allow for a more accurate understanding of material behavior at an architectural scale. A more advanced resolution of the design methods dominated by design modeling is the use of simulation software as a digital form-finding technique through dynamic relaxation (Day 1965).

Form-finding methods are those in which structures define their own shape under applied loads; well-known examples of these methods are the hanging chain models used by Antoni Gaudí for Colonia Güell, and Frei Otto´s experiments on tensile structures, materialized in the Munich Olympic Park for the 1972 Summer Olympics. Although both examples are developed in an analogue round (rather than digital), the mechanisms behind these methods are the ones driving most digital simulation tools applied for form-finding in architecture.

The potential of continual structural evaluation in form-finding allows for the morphology of an architectural system to be informed by physical laws in real-time, enabling the evaluation of multiple iterations of the same system to happen simultaneously. "Digital tools are a powerful ally of design by making, because digital simulations can make and break in no time more models than a physical craftsman could in a lifetime, thus making intuitive, heuristic form-finding by trial and error a viable design strategy. And when a model works, either a physical model or its digital equivalent, there may be no need to know or tell why" (Carpo 2012).

Digital applications such as the one developed by Benjamin Dillenburger for the project *Digital Catenary* (Dillenburger n.d.), or PushMePullMe 3D developed by Gennaro Senatore and Charlie Banthorpe (Expedition Workshed n.d.), allowed for an automation of the loads distribution in a catenary structure, continually calculating the most optimum catenary structure for the given case. However, those projects remain in the realm of the digital, assuming a construction method based on panelization and other post-rationalization methods, where each piece is designed only for a specific part of the structure. The architectural objects resultant of those methods therefore share the lack of construction efficiency of those previously mentioned, falling into the category of modeling design methods "only," rather than signifying a shift in construction methods through the use of novel design and computational strategies.

The project *DigitalPlaster* (fig. 2) by Manuel Jiménez García, Roberto Garcia, Claudia Ernst, and Stella Dourtmes attempts to simplify the design-to-fabrication process, by using a flexible piece as the basic computational element. The use of a collection of instances of these elements (fig. 3) allows for a serial reproduction of the surfaces that conform the structure, while allowing the emergence of heterogeneity. Since the elements conserve their flexibility, the structure could be locally differentiated by altering the connection types or the state of the element anchor points, shifting their physical properties from fixed to free and vice versa. However, in order to optimize the thickness of the resultant shell, and due to restrictions in the material used (fabric formwork for concrete casting), a differentiated thickness along the structure is needed (fig. 4); this leads to a differentiated pattern along the structure, transforming every piece

Figure 1

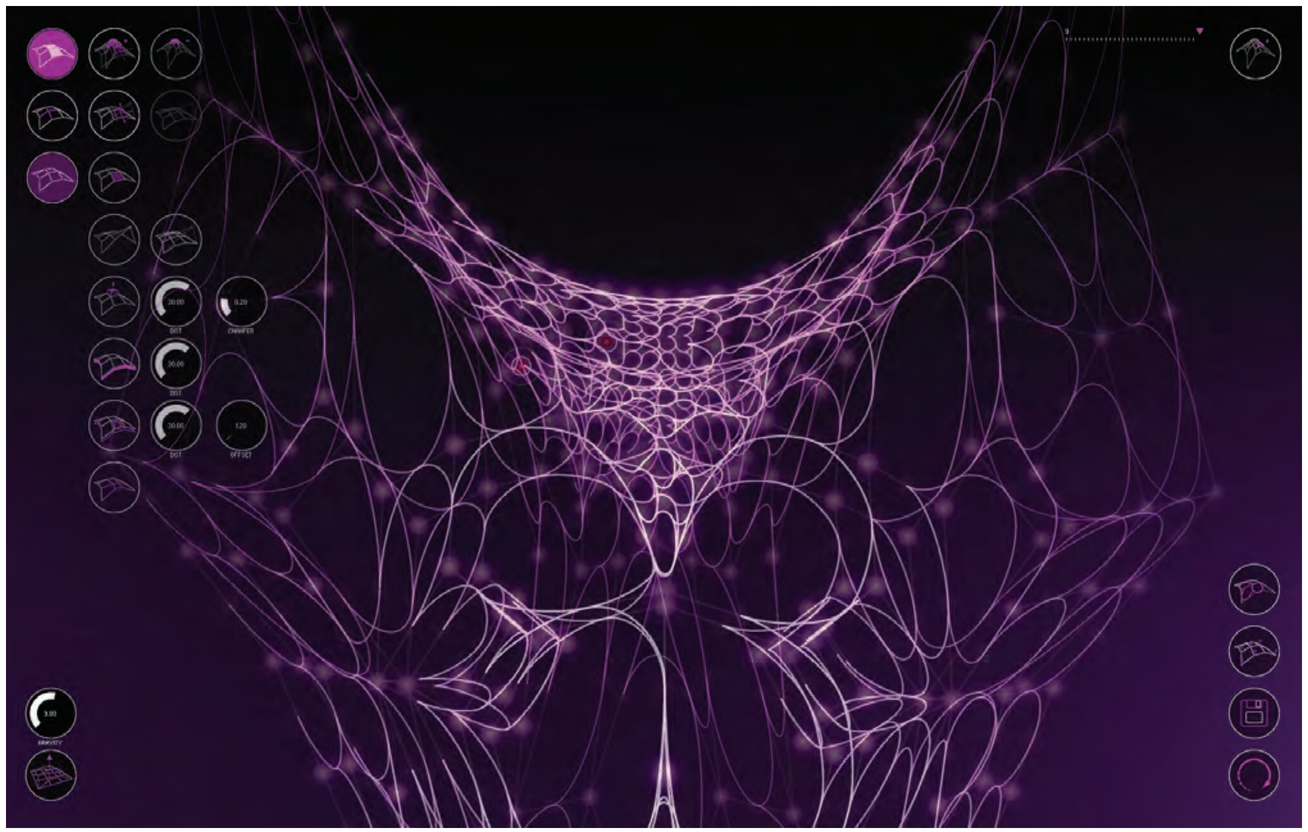


Figure 2

in unique. This step limits the flexibility of the structure and, at the same time, increases construction time and manufacturing cost.

3 TOWARD DESIGNING WITH FABRICATION CONSTRAINTS

In order to develop a design method that would overcome the commonly used post-rationalization process in tensile and flexible structures, the construction element should be embedded in the structure of the modeling and simulation software from early stages of the design process. This initially competes with the design freedom that three-dimensional modeling programs currently offer. The main challenge is therefore to allow the flexibility of modeling techniques, coupled with the rigor of physics simulations and the optimization of fabrication methods.

Working with a reduced family of elements would streamline the design-to-fabrication workflow, avoiding post-processing of any of the individual components of the structure. Structural heterogeneity would be achieved through variability of connections in a combinatorial process, rather than through the mass customization of those elements.

3.1 Poly-Modeling vs Discrete Aggregation Systems

Form-finding methods such as dynamic relaxation are commonly categorized as bottom-up processes. However, the level of setup customization allowed in such methods remains high in relation to other methods commonly used in computational design, such as topology optimization or multi-agent based systems. This categorizes the outputs from form-finding dynamic relaxation as non-fully-emergent, but rather as responsive to structural criteria.

On the contrary, combinatorial methods are inherently bottom-up; each element should find a suitable position in relation to its neighbors in order to form a stable structure when a certain number of elements are fixed. When no external guidelines are established, the system would depend solely on local geometrical conditions and structural evaluation methods (or other criteria) inherent to the system itself. In a combinatorial design method, the designer's agency is shifted to design aspects such as the morphology of the pieces, the local criteria to favor one connection type over another, and the selection of successful combinations. The introduction of external guidelines for these elements is a technique commonly used to gain agency in the design process. These include vector fields to control the main direction of pieces, or bounding boxes to determine the limits of the aggregation, among others. However, the level of flexibility in these design methods is as yet not comparable to the ones present in poly-modelling software.

4 SOFTMODELLING

Softmodelling is an open source Java application, developed to allow a more seamless and efficient workflow between design and fabrication of flexible structures. It aims to offer control over both surface and supporting structure through simple modeling operations similar to poly-modeling software, with the aim maintaining the playful sense of control in such tools.

The software development can be divided into two different stages, each of them focussing on different features currently lacking in most commonly used modeling softwares: The first stage of the software focuses on the seamless integration between poly modeling and physical simulations; while the second stage of its developments aims to create a real-time conversion from mesh faces to discrete linear flexible elements.

4.1 v1.0 – Modeling with Physics

Modeling and animation software often offer physical simulation packages; examples of that range from NDynamics for Autodesk Maya to Mass FX for 3ds Max, or Kangaroo for McNeel Rhinoceros Grasshopper. However, in those cases, physical simulations are considered to be a post-design process. This is due to the software's aim toward animation, rather than form-finding.

When using physics simulation in those packages,

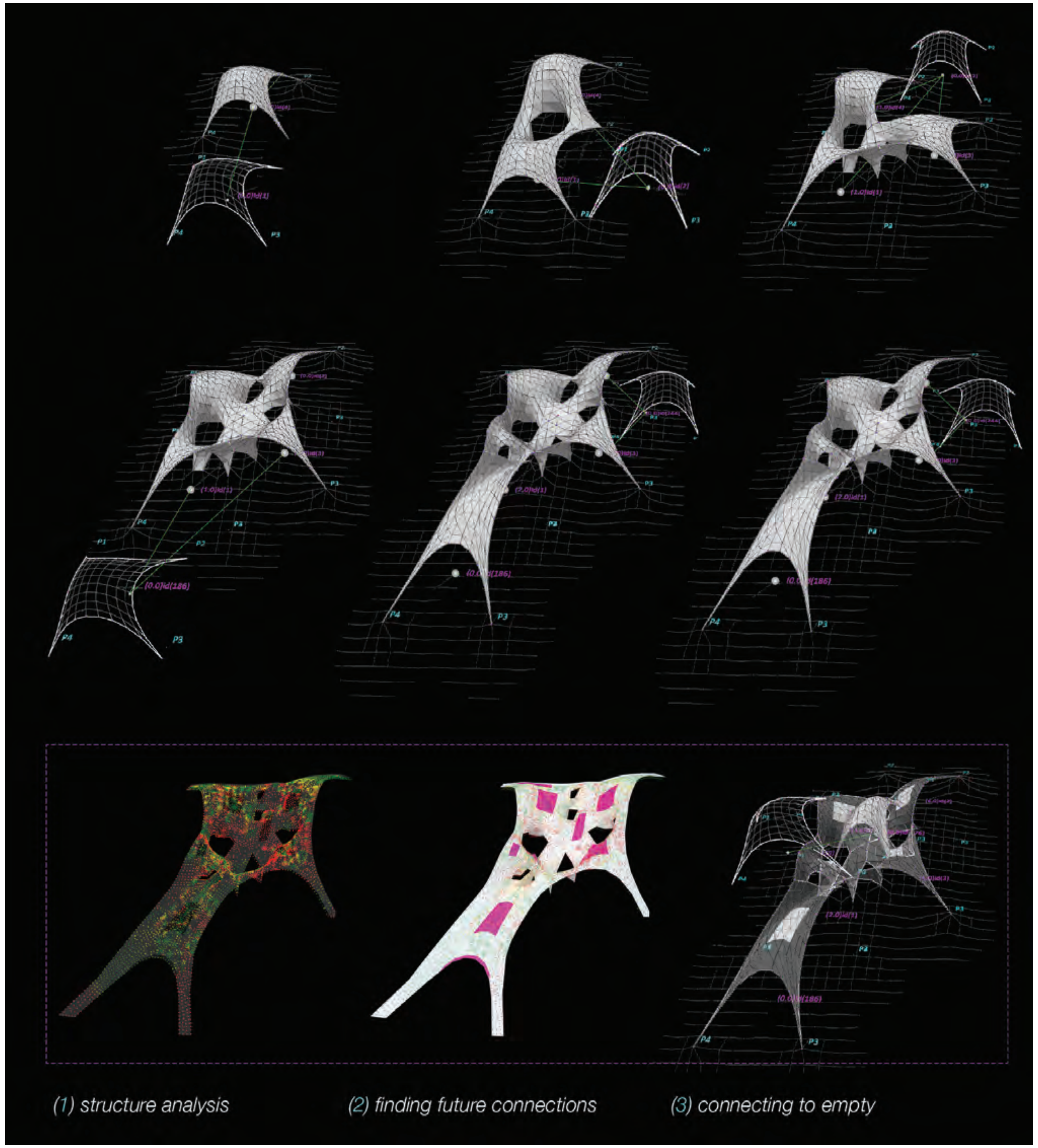


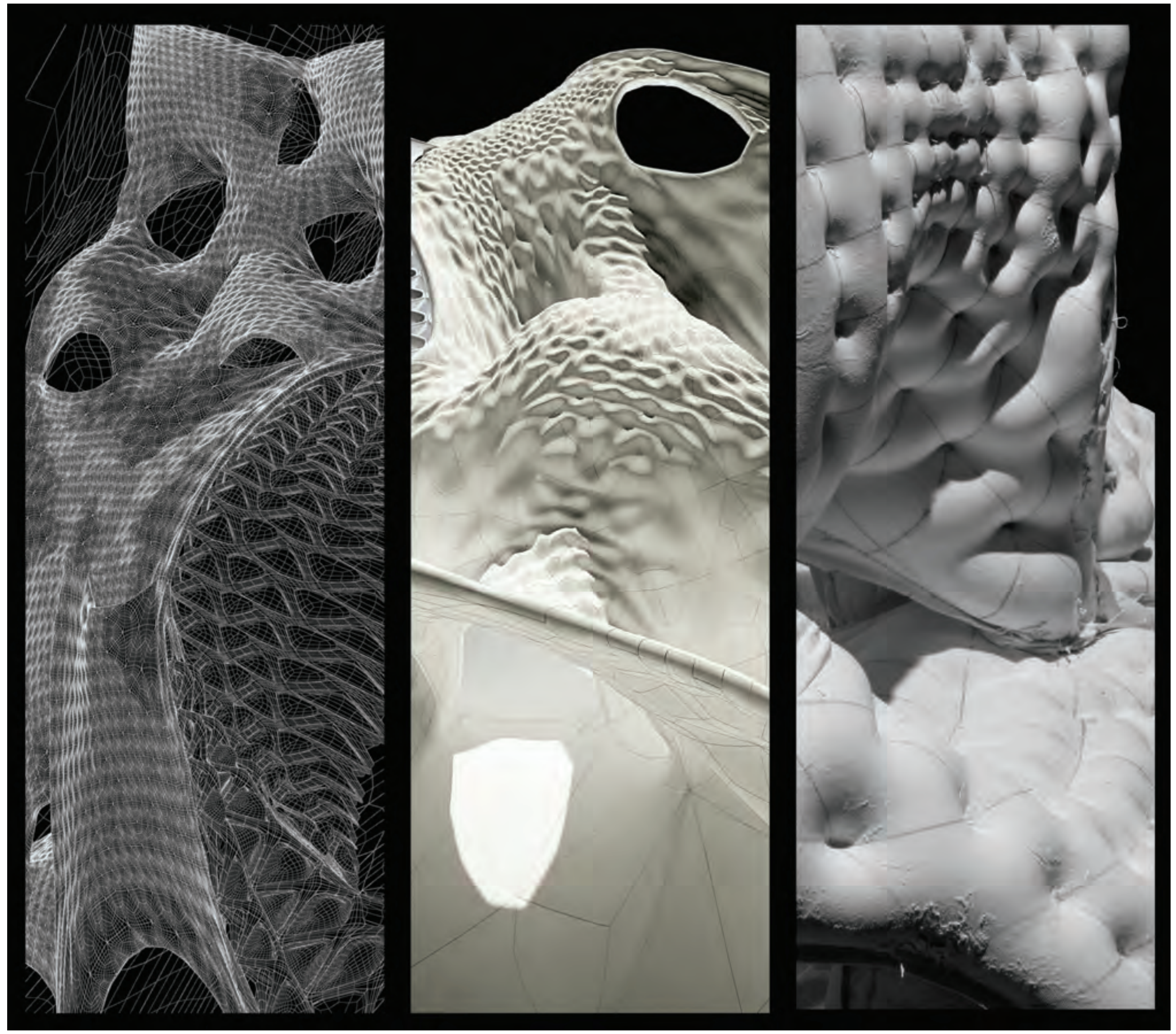
Figure 3

a transformation of the mesh into a particle-spring system takes place. This is a one-way process, which does not allow the performance of any topological operations in the initial mesh after the conversion is completed. This is a result of the mesh structure being recomputed when any modeling operation modifies its topology. The constant shift of vertices and edges' indexes complicates the association of a particle-spring system and the ability to constantly match the new data structure. As a result, these packages do not take into account post physics simulation topologies. After the physics simulation is performed, new vertices will not become particles, as new edges will not become springs. In the case of further topological modification, the return to a pre-simulation stage is required.

Softmodelling is designed to overcome that technical challenge, in order to offer a smoother experience when modeling with physics, using force density methods (Schek 1974). What is modeled becomes automatically "physically active," allowing topological modifications to the object at every step of the design process. This is achieved through the isolation of the affected areas, avoiding the use of computationally expensive processes in the totality of the mesh data structure. New particles and springs are created in the case of face extrusions or subdivisions. In case of subtracting operations, the particle-spring system equally readapts to the new topology (fig. 5).

Once the new data matching process is completed, all elements of the particle-spring system get reconnected to the newly modified mesh. These particle-spring systems therefore become inherent to the mesh itself,

Figure 4



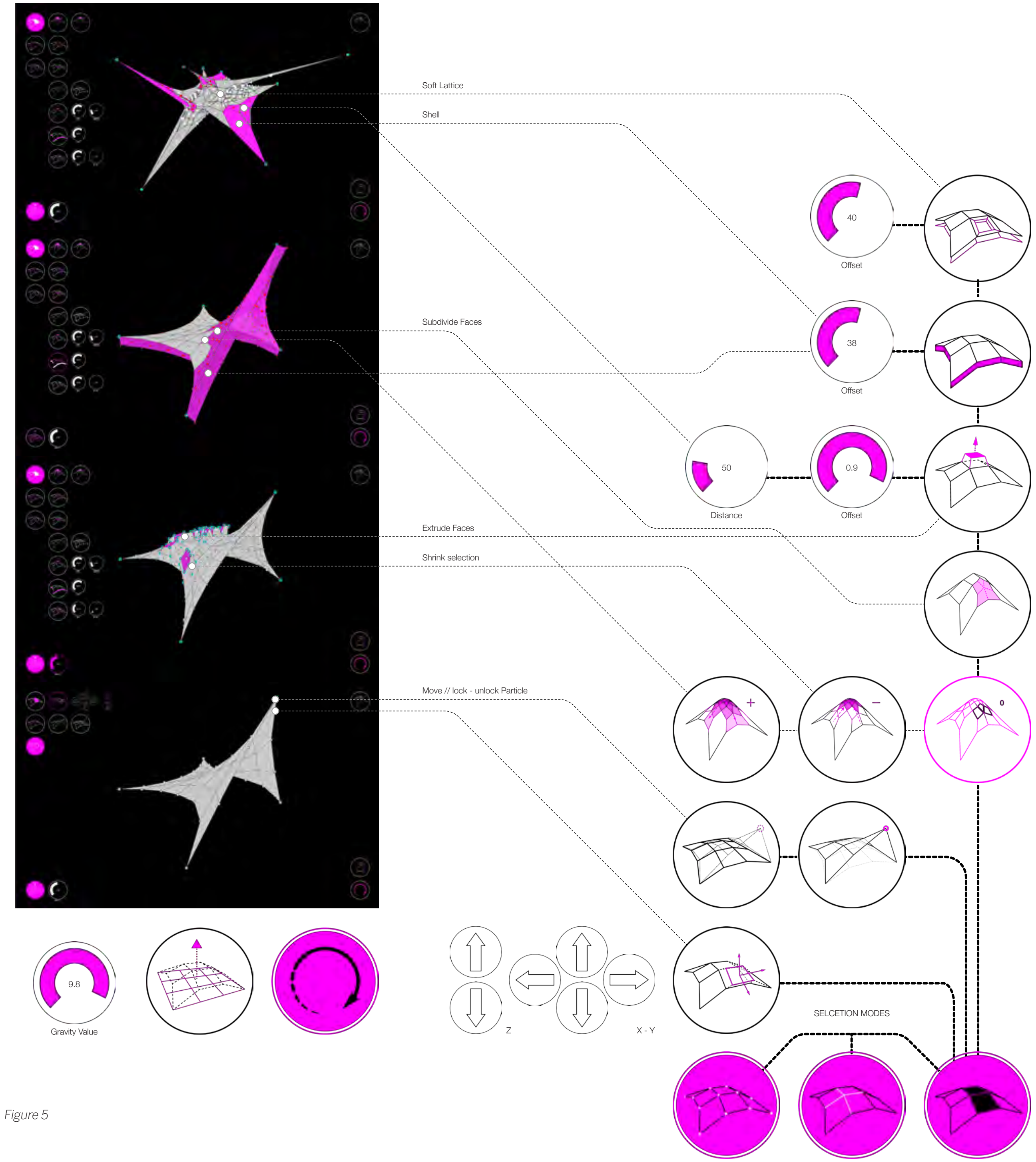


Figure 5

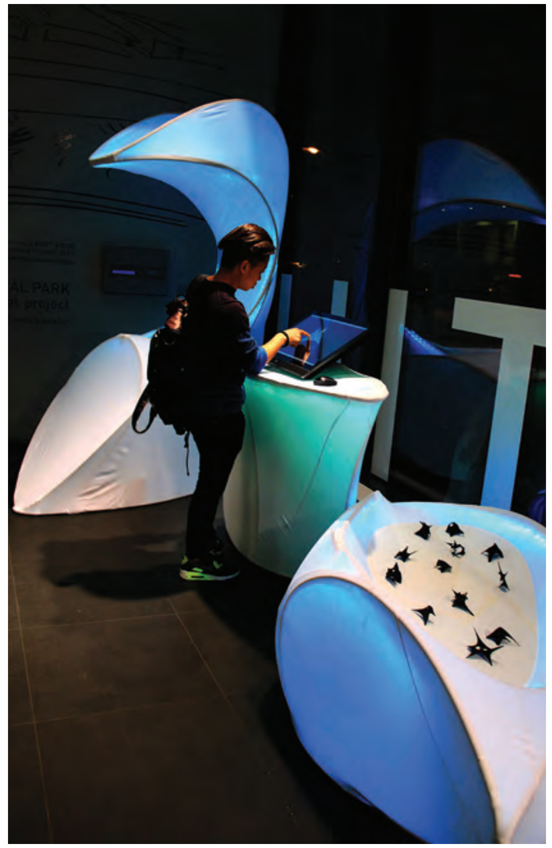


Figure 6

Figure 7

established as a step-by step transformative process. This allows the active modification of the modeled object, enabling its local shrinkage or growth, while maintaining its integrity driven by physical simulation.

4.1.1 Hybrid Flexible Structures

This initial version of Softmodelling was first tested during Resonate 2014 in Belgrade, and officially launched during London's Clerkenwell Design Week (May 2014) at the Actiu London Showroom, where a multi-tactile interface was developed (fig. 6). This allowed participants to test the software and design their own tensile structures during the exhibition (fig. 7).

Since Softmodelling 1.0 only allowed for the manipulation of the surface, leaving aside the structure that supported it, the first large-scale prototypes outputted from the software needed to be hybridized with an intuitive process. The search for structural elements to anchor the tensile membrane was purely based on the addition or subtraction of material along the structure; the digitally generated surface was therefore only used as a reference. There was no extraction of geometrical information from the generated software at that stage; thus, the design method lacked an accurate digital fabrication workflow.

The first large-scale prototypes developed using this version of the software were the trans-computational pavilions created during the AA Visiting School for Architecture Week Madrid at the Official College of Architects (COAM) in 2013 (figs. 8–10) and Roca Madrid Gallery in 2014 (figs. 11–13). Both structures were built with low-cost flexible materials: PVC pipes. All elements had identical length and wall thickness. A differentiated degree of stiffness was achieved through different geometrical combinations of these elements along the structure, rather than utilizing pieces of different properties for each structural requirement. The elements bundled together to create stiffer areas, and branched out to maintain flexibility where stress levels were lower.

A third prototype was tested during the Clerkenwell Design Week 2015 (fig. 14), where a better design-to-fabrication workflow was established. However, the lack of precision in the creation of linear structures from the general topology in Softmodelling 1.0 led to a tedious post-rationalization process to fabricate the piece.

Regardless of the lack of continuity between the digital model and the physical prototype, the process of searching for different combinations of elements to achieve a differentiated stiffness along the structure was instrumental for the development of future versions of the software. Links between material density, connectivity, and surface performance continued to be established. Following stages of the software attempt to rationalize those links in order to create computational strategies for the creation of both surface and frame simultaneously.

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

4.2 v2.0 – Discrete Flexibility

The plethora of functions in an architectural object leads in most cases to the use of different materials with different strengths, porosities, opacities, etc. These are as well shaped to respond to specific conditions within the architectural object. It is therefore extremely challenging to create an entire building out of one material only, or out of a short material pallet. In those cases where a reduced material pallet is used, the level of specificity of the different parts usually translates into highly customized manufacturing processes.

This is especially relevant when using flexible materials. The most well-known examples of flexible architecture—*Instant City*, designed by José Miguel de Prada Poole (Ibiza, Spain 1971), *Wayback Machine* by Haus-Rucker-Co (1968), and the *Cushicle and Suitaloon* by David Greene (1964–67)—emerge through the use of patterning as an essential tool for controlling material deformation, and therefore transform parts made out of the same material into doors, floors or ceilings, and other architectural elements. This is also the case of the aforementioned project *Digital Plaster*, where pattern density was linked to structural requirements at every point of the structure.

In addition, flexible materials are hard to simulate accurately. Particle-spring systems, commonly used for the simulation of flexible structures, are indeed computationally expensive processes. When the variety of

Figure 13

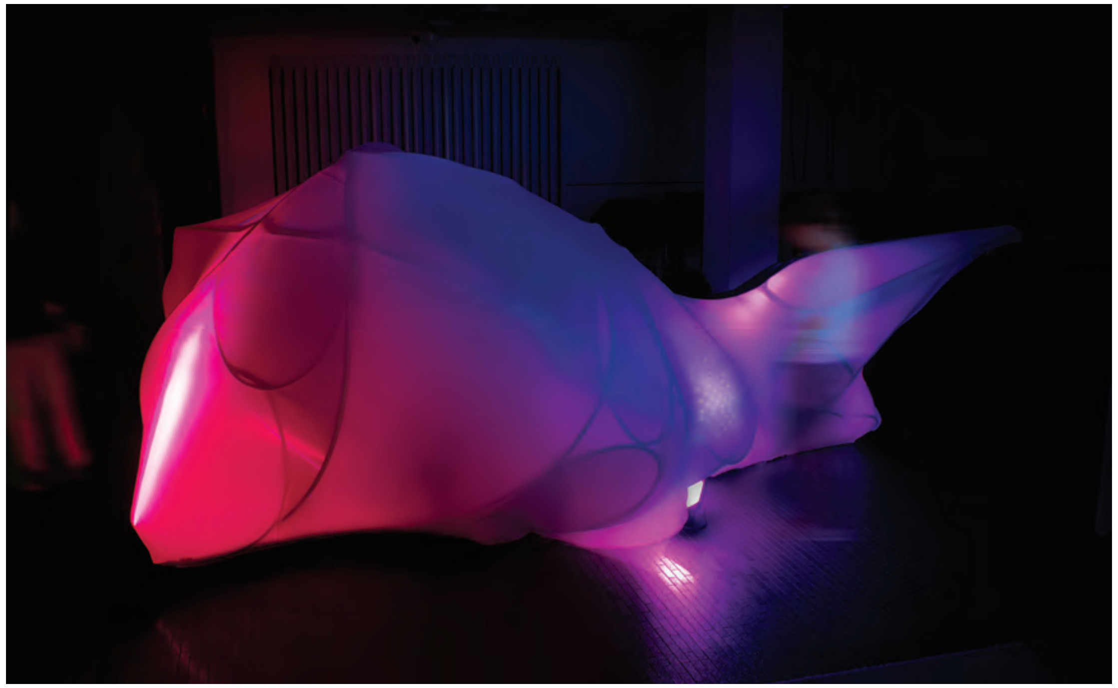


Figure 14

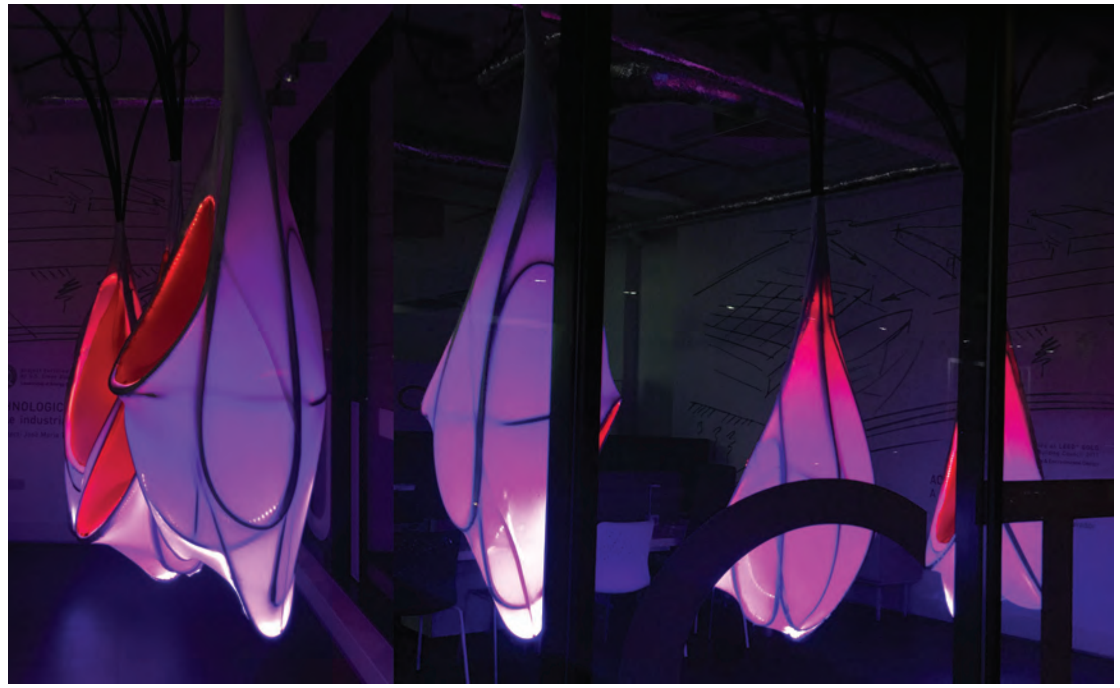
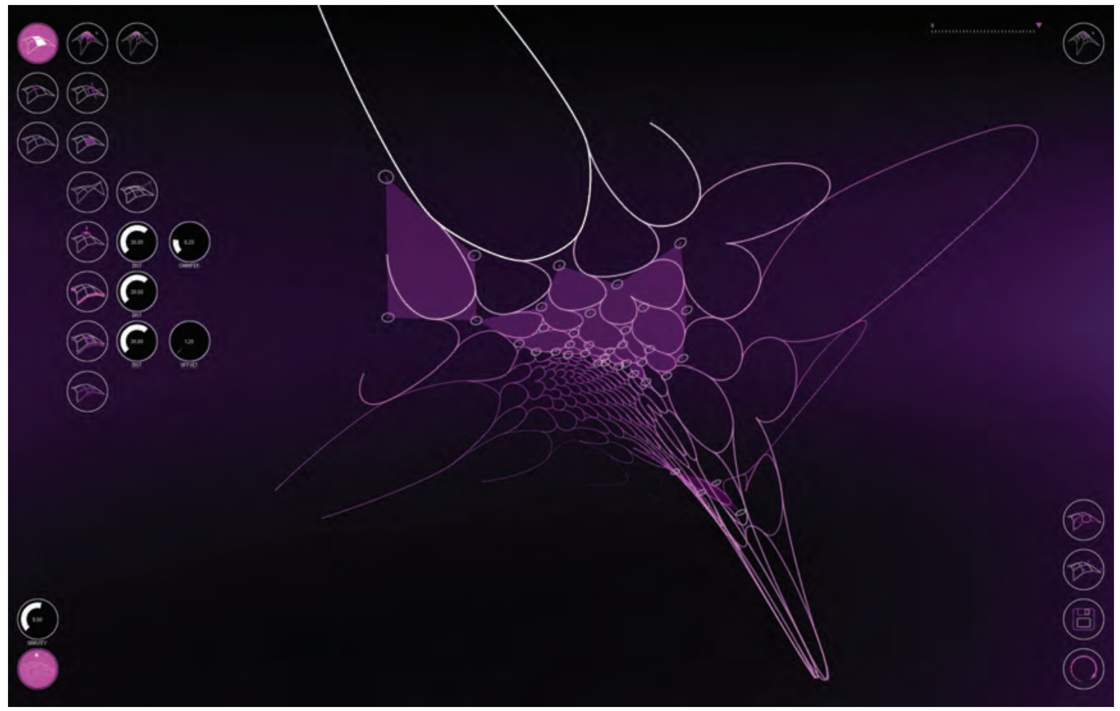


Figure 15



pattern types within the structure is large, the level of computational power required for the simulation process becomes exponentially higher. Softmodelling 2.0 introduces a discrete approach to the design and manufacture of flexible structures at an architectural scale. This aims to not only reduce computational complexity in the simulation, but also speed up the fabrication of the architectural elements.

In mathematics, “discrete” refers to the study of elements that don't vary smoothly, but have distinct, separated values. In the field of design, Neil Gershenfeld argues the need for digitizing not just the design but also the materials (Gershenfeld et al., 2015). In this context, The Centre for Bits and Atoms has developed the notion of digital materials—parts that have a discrete set of relative positions and orientations (Gershenfeld et al., 2015). These materials are able to be assembled quickly into complex structures. This has proven to increase the efficiency in the production of large elements, since the shift from customization to assembly leads to a simpler automation of the manufacturing process.

An example of this shift in computational design methods is the research that Manuel Jiménez García, Gilles Retsin, and Vicente Soler developed at The Bartlett School of Architecture UCL. Their latest prototypes aim to prove that “discreteness can make the automation of construction processes more efficient while also allowing for more complexity and differentiation” (Retsin et al., 2017).

Regarding flexible structures, some of the most successful attempts to conform structurally stable prototypes have implied the use of discrete design methods. That is the case of *Jonah's House* by José Miguel de Prada Poole (1968), in which identical cells are used in order to facilitate the assembly process and, at the same time, allow the control of air-pressure in each cell individually. This allows the elongation or reduction of the wall thickness locally along the entire structure.

As previously discussed, the latest version of the software incorporates the control of the discrete elements that conform the structure, aiming to produce a coherent workflow from the membrane modeling to the fabrication of both surface and structural frame. This development focuses, therefore, on the combinatorial process of discrete flexible linear elements, rather than in the isolated manipulation of the tensile membrane. This comes as a necessity from the experience with the prototypes developed with Softmodelling 1.0, which highlighted the importance of a computational strategy which would allow a further control on the elements that conform the structure.

A discrete approach is used, where instead of post-rationalizing the surface into thousands of different panels, three different lengths of flexible lines are adapted in the most suitable combination to establish a symbiotic relationship with the membrane. This leads to the creation of a reciprocal structure, in which both frame and membrane work in conjunction to create structural stability (fig. 15). The distribution of discrete pieces is linked to the faces of the mesh, in order to preserve the intuitive nature of a poly-modeling software. Therefore, transformations in the topology of the mesh affect the distribution of the linear elements that support it.

In order to prove the viability of the workflow in an

Figure 16

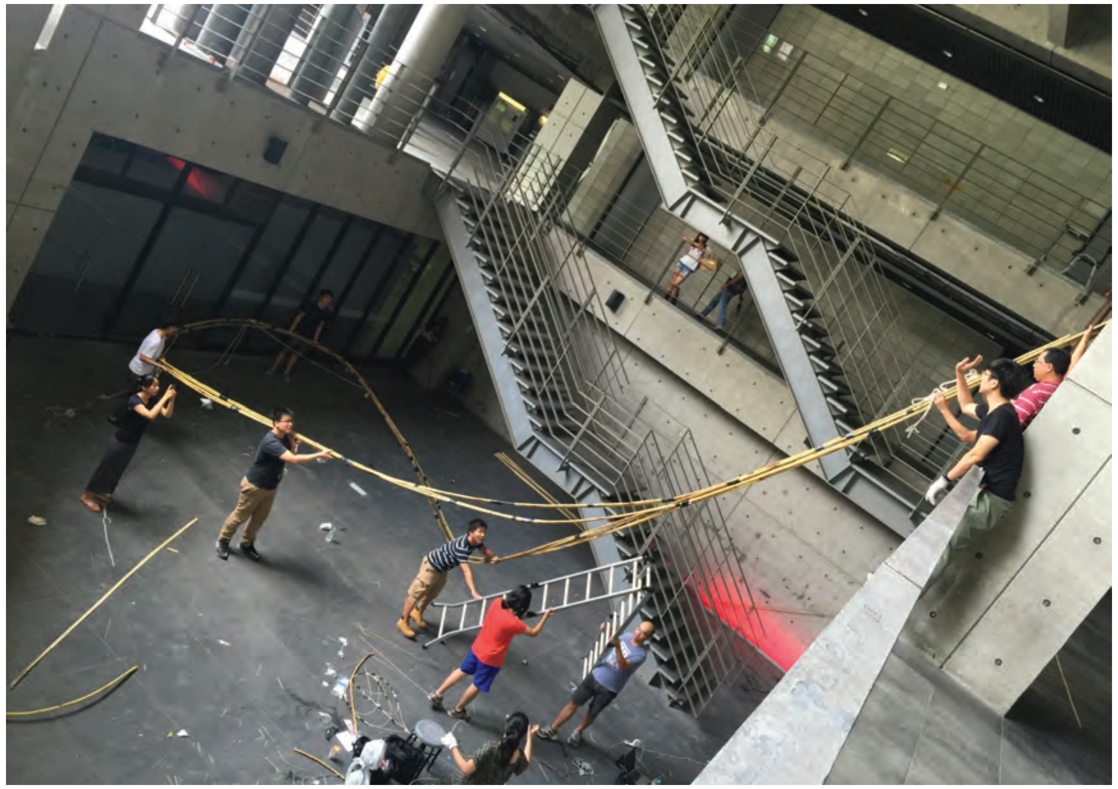
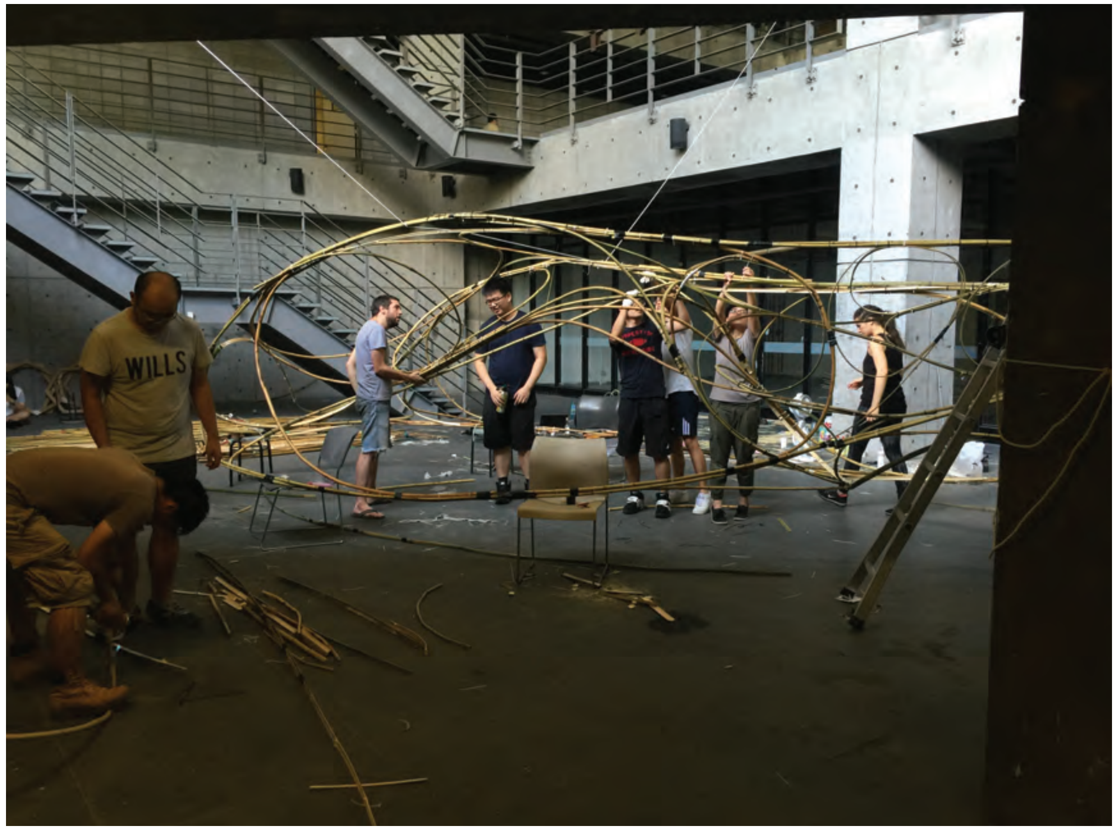


Figure 17



architectural scale, a series of physical prototypes where developed. These isolate the linear elements to assure structural integrity without the internal tension that the tensile membrane added in previous projects.

Materials with different degrees of flexibility were tested in this stage; analyzing each of the materials' performance would improve the versatility of the software as a design tool.

4.2.1 Natural Bending Active Structures

The first physical outputs of this stage of development make use of bamboo pipes as main building elements. Bamboo is a natural material with a high breaking strain; this leads to an "extensive use of active bending in the constructions of vernacular architecture across cultures and continents" (Lienhard 2013). Even though this material has a much higher strength, the geometrical constraints to control local stiffness do not deviate excessively from the ones that governed the PVC structures explored in previous installations.

The first of these installations, entitled *Offshore Bezier,* was developed as a commission by Shih Chien University (Taipei, Taiwan), in collaboration with Christina Dahdaleh. It was first exhibited during DEZACT Extra Fabrica 2015. The project was conceived as a prototype to understand the material behavior when used under different bending forces. The aim was to utilize the abstracted behavioral data in future stages of Softmodelling, allowing the development of a digital-to-fabrication workflow through the assembly of linear bamboo elements. At this stage, Softmodelling was only used as a design tool, with no aim to control the fabrication process through the software itself. The digitally designed structure was taken as a loose fit reference geometry. Bamboo elements were bent to approximate the linear bundles outputted from the software. The deviation from the digital model to the physical prototype allowed for a better understanding of the maximum radius endured by the material before reaching its breaking strain (fig. 16).

At the same time, structural stability was tested at every step of the assembly process. This allowed to easily perceive the necessity of stiffer areas along the object, as well as to identify the parts of the structure that could remain more flexible. These conditions influenced the build-up of the installation, where elements were added or removed throughout the fabrication process to respond to structural requirements (fig. 17).

Regardless of the lack of a clear design-to-fabrication workflow, the approximation of the structure initiated by Softmodelling was proven to behave within the material limitations at most stages. A more accurate digital simulation of the bending moments in the structure will be developed in future stages of this research (figs. 18 and 19).

The installation entitled *Woven Memory*, designed in collaboration with Christina Dahdaleh and Wei Chieh

Figure 18

Figure 19

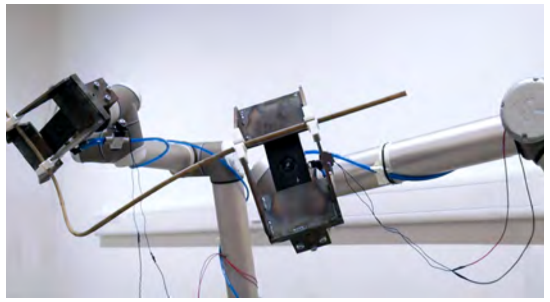


Figure 20

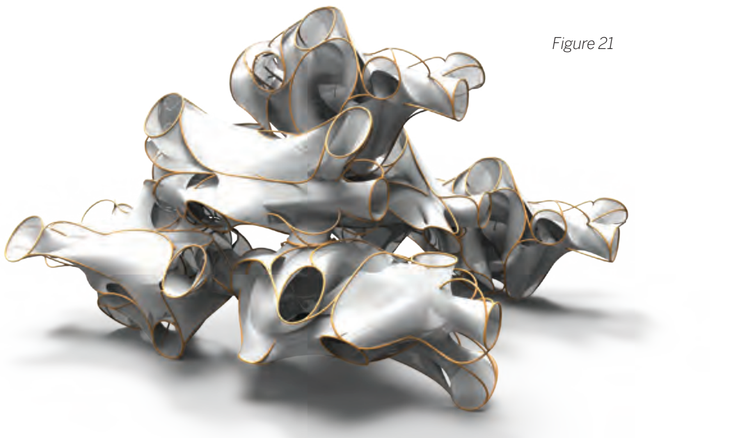


Figure 21

Shih for DEZACT Space Media Festival 2016 (National Taiwan University of Science and Technology, Taipei, Taiwan), made use of Softmodelling not only for computing flexible materials, but also to output fabrication instructions, establishing the first design-to-fabrication workflow in this research.

Universal Robots were used to bend linear bamboo elements and to assemble these bent elements into a stable structure. This process was established through a workflow dictated by Softmodelling and ElasticSpace, a custom-made application developed by Keiichi Suzuki Erazo, which focuses on physical simulation of active bending structures. The robotic bending workflow was developed by Alvaro Lopez and Vicente Soler at The Bartlett School of Architecture UCL Design Computation Lab.

The element was shaped by two bending end effectors mounted on two UR robots working synchronically. This allowed the translation of each digitally simulated curve into a dual robotic tool path which controlled the position and angle of the curve end segments. Simulation techniques were again applied to approximate the digital model to the material deformation, leading to the optimization of the bending process from just the initial and end segment of the bamboo element (fig. 20).

The pavilion was formed by a collection of six modules (fig. 21), which embed the same information as the overall structure. They integrated three to seven flexible linear elements, which bundled together to create a light-weight framework to house the ink impregnated fabric (fig. 22).

The structure was then disassembled and rearranged for the Modern Body Festival at The Hague in December 2016 (fig. 23). This process involved the relocation of the singular elements into identical groups (fig. 24), which would connect to other instances to create larger clusters (fig. 25). Those clusters where finally assembled into a larger structure, which served as a canvas for a laser performance by Wei Chieh Shih during the opening event.

4.2.2. Mix-Flexibility

The latest trans-computational pavilion, developed in 2016 for a temporary exhibition at the Official College of Architects (COAM) in Madrid, aimed to investigate the use of multiple materials with different degrees of flexibility. The design workflow was developed using Softmodelling and ElasticSpace as the main design tools, allowing the coexistence of an active bending structure, materialized with fiberglass rods and a passive, robotically bent network of elements. The decision of the material used in each part of the structure is related to the amount of tension and compression in specific parts of the elements (figs. 26 and 27)

Figure 22

Figure 23

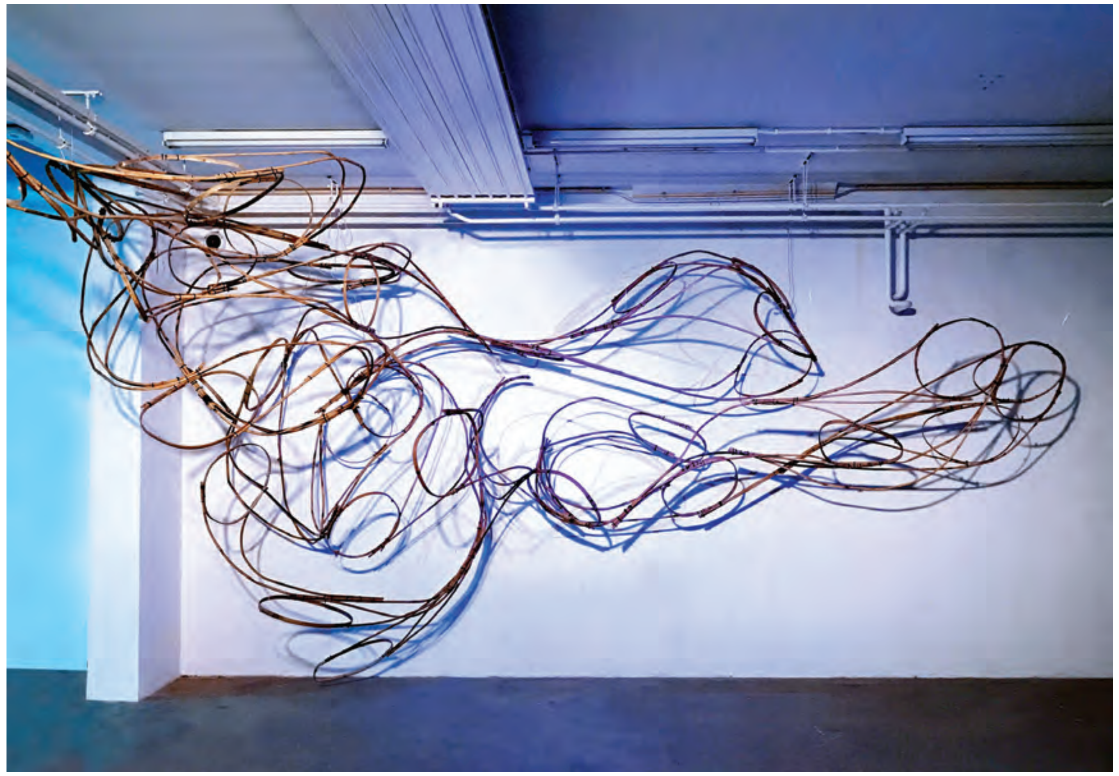


Figure 24

Figure 25

Two ABB 1600 robots, equipped with custom-made end effectors were used in multi-move mode to bend 600 identical aluminum bars of 1.5m each in just 48 hours (fig. 28). These were assembled together in a larger object, conforming the static part of the structure.

Due to the lack of material feedback developed for automation of the assembly process, both fiberglass and aluminum discrete pieces were assembled manually. However, the simulation was proven to have the right level of accuracy to predict the material deformation. This allowed for the computation of both material systems in the same digital model.

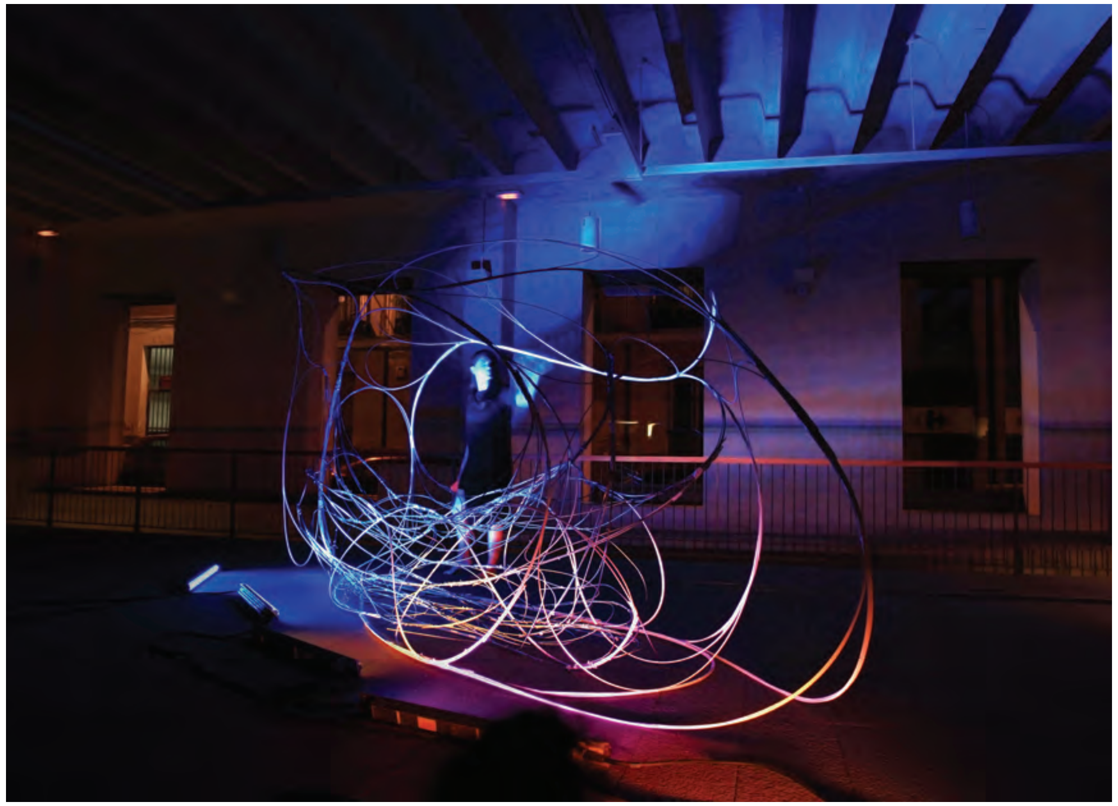
Future developments of this research will explore controlling the control of local stiffness of both systems locally, through the different arrangements and levels of connectivity between them.

5 CONCLUSION

The computational methods developed in Softmodelling have significant implications for the design and fabrication of large-scale structures through the use of flexible materials. The feedback loop between poly-modeling and physics has proven to simplify the manipulation of flexible materials in the digital realm. Furthermore, the addition of a fabrication module in the latest versions of the software has established a more efficient workflow, while also enabling higher degrees of complexity in material organizations.

Enabling the use of such computational design and

Figure 26



manufacturing methods configures a new take on the ideas about flexibility initiated in 1960s and 1970s by Haus-Rucker-Co, José Miguel de Prada Poole, and David Green, among others. Although both design and manufacturing with flexible material are still difficult to control, the tools developed in this research prove to increase efficiency in a design-to-fabrication workflow, streamlining the production of such structures. This could enable the industrialization of flexible architectural elements, increasing the accessibility to this process and therefore its utilization in larger projects.

The discrete method initiated in the latest version of Softmodelling increases the efficiency of both computation and fabrication; it also decreases the gap from digital simulation to the physical prototypes. However, the software still has a large number of dependencies from other tools that help in the simulation of the bending active elements, and this limits its flexibility. Further development of this research will include bending simulation inside the software. This will be achieved through the dissociation of the faces from the frame structure, while maintaining the control of one from the other. This will enable the direct translation from the geometry generated in Softmodelling to the robotic tool paths for the fabrication of the elements. The prototypes generated during future stages will therefore aim to reduce the amount of intuitive human intervention, allowing for a higher degree of automation on the construction of flexible structures.

Figure 27

REFERENCES

Carpo, Mario. 2012. "Digital Darwinism: Mass Collaboration, Form-Finding, and The Dissolution of Authorship." *Log*, no. 26 (Fall): 97–105.

Day, A.S. 1965. "An Introduction to Dynamic Relaxation." *The Engineer*, vol. 219 (5688): 218–21.

Dillenburger, Benjamin. n.d. "Digital Catenary." https://benjamin-dillenburger.com/digital-catenary.

Expedition Workshed. n.d. "PushMePullMe 3D." Developed by Gennaro Senatore and Charlie Banthorpe. https://expeditionworkshed.org/workshed/push-me-pull-me-3d/.

Gershenfeld, Neil, Matthew Carney, Benjamin Jenett, Sam Calisch, and Spencer Wilson. 2015. "Macrofabrication with Digital Materials: Robotic Assembly." *Architectural Design*, vol. 85 (5): 122–27.

Lienhard, Julian, Holger Alpermann, Christoph Gengnagel, and Jan Knippers. 2013. "Active Bending, A Review on Structures where Bending is used as a Self-Formation Process." *International Journal of Space Structures*, vol. 28 (3–4): 187–96.

Retsin, Gilles, Manuel Jiménez García, and Vicente Soler. 2017. "Discrete Computation for Additive Manufacturing." In *Fabricate 2017*, edited by Achim Menges, Bob Sheil, Ruairi Glynn, and Marilena Skavara, 178–183. London: UCL Press.

Schek, H.J. 1974. "Force Density Methods for Form Finding and Computation of General Networks." *Computer Methods in Applied Mechanics and Engineering*, vol. 3 (1): 115–34.

Stallman, Richard M. (2001). "Free Software: Freedom and Cooperation" Transcript of speech presented at New York University in New York, NY on 29 May 2001. https://www.gnu.org/events/rms-nyu-2001-transcript.txt.

Ward, Jonathan. 2010. "Additive Assembly of Digital Materials." PhD thesis, Massachusetts Institute of Technology.

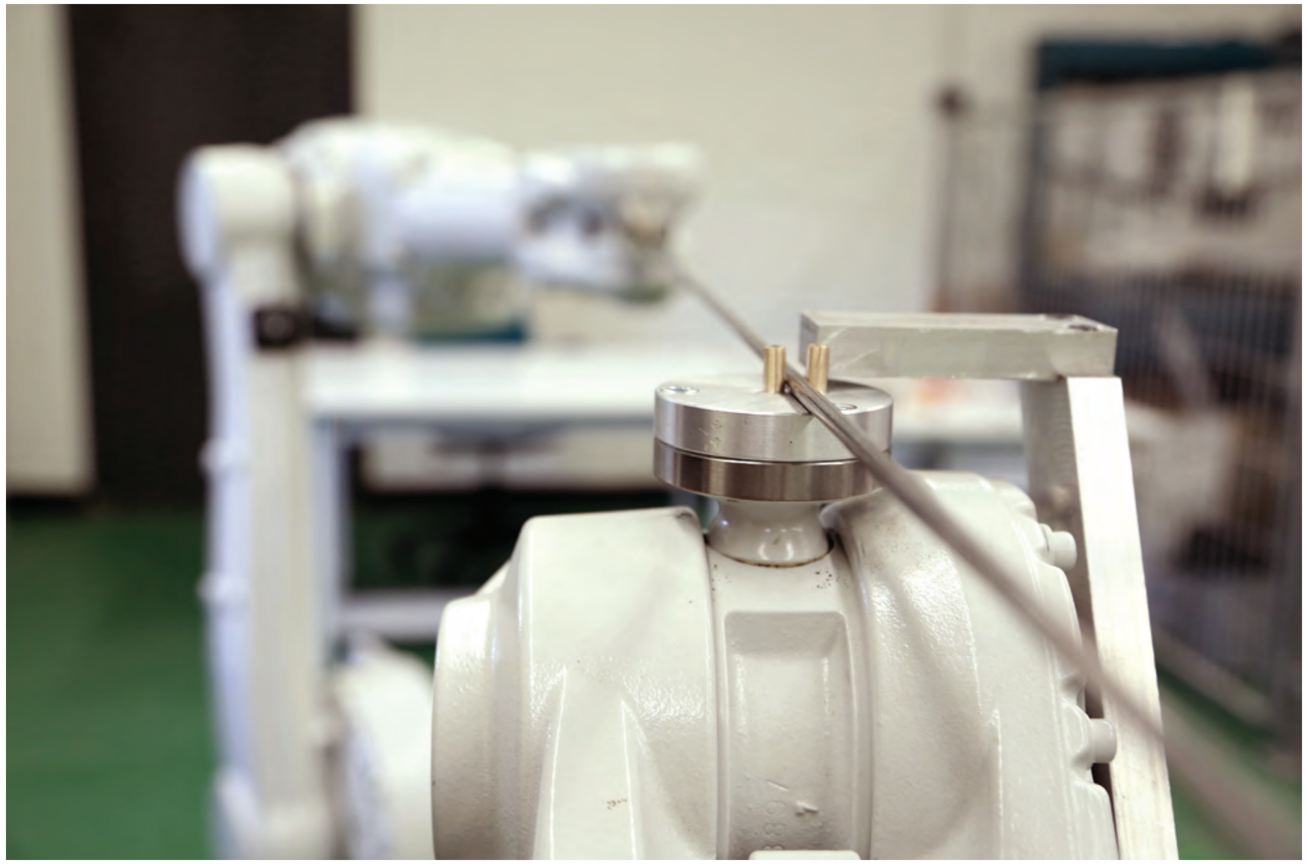


Figure 28