# Case Specific Robotic Fabrication of Foam Shell Structures

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*Most recent developments in the design of free form shells pursue new approaches in digital fabrication based on material properties and construction-aware design. In this research we proposed an alternative approach based on implementation of expanded polystyrene (EPS), a non-standard material for shells, in the process of industrial robot fabrication that enables fast and precise cutting of building elements. Main motivation for using EPS as a building material was driven by numerous advantages when compared to commonly used materials such as: recycleability, cost-efficiency, high earthquake resistance, durability and short assembly time. We describe case specific fabrication approach based on numerous production constraints (size of the panels, limited robot workspace, in situ conditions) that directly design the process.*

**Keywords:** *computational design, shell structures, robotic fabrication, hot-wire cutting, multi-robot control*

## INTRODUCTION

The concept of using curved surfaces in contemporary architectural practice has been increasing in the last decade. With this interest, the field of architectural geometry has been developing, including the geometry of shell structures as well. While thin pavilions, experimental structures and shells serve as vehicles for developing future concepts of architecture through the employment of new materials, fabrication techniques and design strategies, they also bring new solutions. The reason for using shell structures as pavilions is due to its self-supporting ability, low cost and material consumption, while the improving various research methods ease up the process. Research methods pertain to structural optimization, material application, various tessellation, fabrication, assembly approaches and in situ conditions. New advances in architectural geometry allow for adequate analysis and simulation of shell structures, thus generating a structurally informed model (Richardson et al, 2013). Such a model is used in an integrated approach to indulge all the requirements of above mentioned areas. Integrated design, in this research, refers to integration of various fields of expertise, including design, fabrication, material properties, assembly and transportation, in order to procure a precise and valid solution to a predefined set of parameters in the early stages of the design process. Referred to as "fabrication-aware design", it emphasizes the necessity of the design and fabrication connection (Wu & Kilian 2016). It is fundamentally about removing the fissure between the processes that bring forth a design and the operations that will lead to its fabrication (Pigram & McGee, 2011).

For example, tessellating a surface can be done with regards to the size of the model and the panels (Wang et al,2014) as well as the size and capabilities of the fabrication tools and machines (La Magna et al, 2016; Rippmann et al, 2016) and the material being used (Block Research Group, 2012, Rippmann & Block, 2011a). Furthermore, with inclusion of cost-effectiveness as a condition, the tessellation can be done with planar panels that have a major impact on the entire design (Eigensatz, 2010). Structural integrity is also used as a tessellation guideline, generating panels with connecting faces oriented perpendicular to the surface (Rippmann & Block, 2011b). Fabrication conditions, such as hotwire cutting, influence the panel generation by using ruled surfaces (Pottmann et al, 2008), and thus the path the machine needs to follow in order to fabricate the panel (Wang & Elber, 2014).

The assembly is the end of such a process, but still an inseparable part of the integrated approach. In order to grasp the magnitude and the complexity of the project and fabricate it, it is necessary to generate a proper workflow. The problem, which this paper focuses on, is when the conditions for the fabrication of the architectural structure are not ideal and hence it is necessary to find the way to satisfy the requirements of the project with the capabilities available. In this paper, fabricating a real-size shell structure out of expanded polystyrene (EPS A100) is presented and the goal of the research is to find a proper workflow that adjusts to in situ conditions and available equipment on one side, and project requirements on the other.

## *PROJECT REQUIREMENTS*

The pavilion was made for the European Research Night, where the main topic was cool science. Therefore, for the topic of architecture, building a shell structure resembling an igloo was chosen, based on novel fabrication methods. The available space was set to as no more than 8x8m in floor plan area. The assembly process had to be finished in 12h or less, since the in situ conditions dictated that the Igloo may not be placed before the start of the manifestation, which implied prior partial assembly and transportation. Furthermore, the parts had to be light-weight, demountable and easily transportable to allow for multiple assemblies on different location. Taking into account the size of the building's entrance, and the prior assembly area, the parts had to be no more than 2m in any direction. The necessity of the visitors to learn and acquaint themselves with the project, and be able to move through it, showed that a classical approach to generating an Igloo was inadequate. Therefore, the Igloo needed to be designed with at least two entrances, and 2m in height to serve as an unrestricted passageway. The funds for the material application were limited which influenced its choice. Using expanded polystyrene as a material of choice proved to be prudent, for its lightweight properties, color, low cost, easy cutting, shape and size manipulation. The equipment used for the hotwire cutting process were two ABB IRB 140 industrial robots and a hotwire cutting tool 40x40cm in size. After the project requirements were laid out, the integrated design approach and workflow followed.

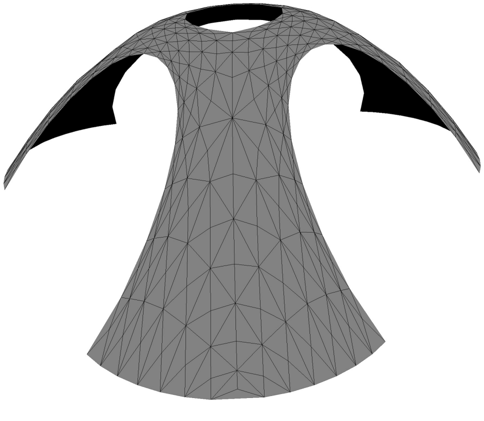

Figure 1
The depiction of the structure as a mesh model procured by RhinoVault application

## THE WORKFLOW

The workflow needed to be generated with early integration of all viable areas of interest, necessary for the adequate completion of the structure. Important areas included the form generation, then tessellation with regards to the choice of material and the fabrication tool and process, the fabrication process itself, the assembly, transportation and (de)mounting on site. Project requirements influenced each of these interest zones and presented omnipresent conditions that limited and guided the solution to the end, accompanied with contemporary methods and techniques. The starting point was generating the form, since all other areas of interest depended on it.

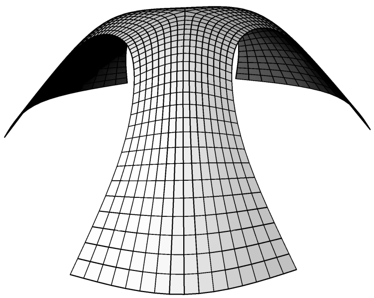

Figure 2
The depiction of the structure as a NURBS model procured by means of converting polylines into NURBS curves and generating a surface

### *FORM GENERATION*

Given the latter and following the conceptual appearance of shell structures, a Y floor-plan shape was taken as a starting point, offering 3 possible passages for the visitors with varying passage heights. A hole was placed on top of the shell, in order to show the potential that shell structures have when transferring load through narrow sections and to give people the sense of openness when going through it. In order to generate a self-supporting shell structure, RhinoVault plug-in for Rhinoceros software was used. Following the project requirements, the mesh model was obtained, which served to guide the rest of the process (Figure 1).

Since, a model with smoother surface continuity and curvature fairness was necessary in order to acquire a more precise tessellation procedure, the mesh model was sectioned into horizontal polylines for each prong, which were converted into degree 3 NURBS and used for generating a NURBS surface (Figure 2).That model was used for generating the tessellation procedure following the fabrication tool and process choice.

### *FABRICATION TOOL AND PROCESS*

Implementing an integrated design approach demands that all processes be taken into consideration in reference to one another. The tessellation process had to be done with consideration to the material application and affordability, capability and size of the fabrication machines. In contemporary practice, hotwire cutting and CNC milling are the preferred fabrication approaches when using Polystyrene as a material of choice.

CNC milling is a time consuming process, it causes a large amount of residual waste in form of small unrecyclable particles and the panel size is determined by the machine's work area. On the other side, by applying hotwire cutting, the residual waste material is in recyclable parts, and he process can cover a larger percent of the panel in reference to the time consumed. Hotwire cutting can be up to 126 times faster when compared to adequate milling processes (Brander et al, 2016a) and even faster than that (McGee et al, 2013). The level of details less when compared to milling. Hotwire cutting is used by CNC machines with 3 degrees of freedom in contemporary practice for cutting out desired parts from larger Polystyrene blocks. By implementing industrial robots with 6 degrees of freedom, the fabrication process can be upgraded. It is even used for changing the profile of the curve during the cutting process to achieve greater level of detail in surface generation (Brander et al, 2016b; Rust et al, 2016b ). That is why robotic hotwire cutting was chosen as the fabrication process. However, there was a great inconsistency between the size of the Igloo, which was 2,2m high

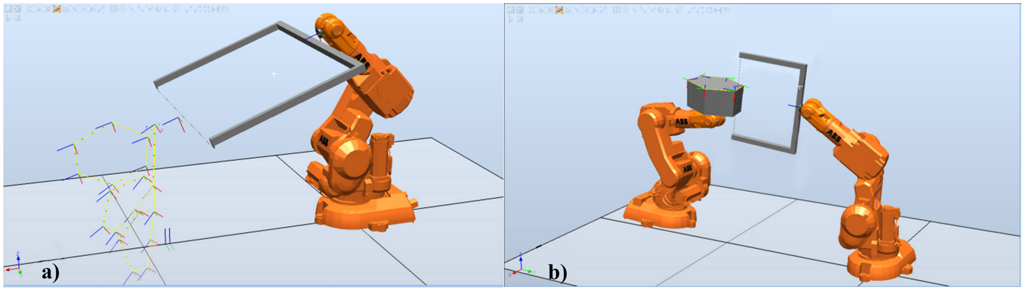


Figure 3
Two approaches to fabricating the panels a) enlarging the hotwire tool for a single robot to perform the cutting process b) two robot setup where one holds the piece and the other uses a smaller hotwire tool for cutting the elements

and spanned for 8m and the size and working area of the available industrial robot (ABB IRB 140), which was around 1m.

This indicated that the tessellation procedure had to yield properly sized panels in order to accommodate for the size discrepancy. However, having a large number of small panels would complicate and prolong the assembly process, where minor fabrication errors would build up to larger ones during the assembly. Two options were possible:

- The first one was to enlarge the hotwire cutting tool (up to 60x70cm) for a single industrial robot (Figure 3a), thus enabling the enlargement of the panels, decreasing their number, but in the process limiting and decreasing the robot's dexterity. Furthermore, the cutting error would exist due to the length of the fork holding the hotwire, which would vibrate due to the high speed rapid changes in the cutting path direction, meaning that the speed of the changes would need to be minimal.
- The second option was to use two robots of the same type in a conjoined fabrication approach, where one would hold the piece and rotate it, and the other would use a smaller hotwire cutting tool (40x40cm) to cut the outside ribbon (Figure 3b). This is an innovative way of overcoming the size discrepancy between the panel and the working area of the robot and the tool combined. In such a way, a larger panel could be produced more precisely without the error due to the tool. This approach demanded a proper calibration between the two robots, enough space to maneuver and the necessity to cut the Polystyrene block to size to fit onto the robot, which demanded more time than the first option.

In the end, a hybrid approach was chosen, where sufficiently large panels, spanning beyond the size of the larger hotwire cutting tool were fabricated by using the conjoined approach, while the rest was fabricated following the first approach, which was already tested in previous research (Jovanovic et al, 2017).

## *THE TESSELLATION PROCEDURE*

Following the decision, the shape and the size of the panels had to be determined. Taking the refined digital model as a starting point and using the Evolute tessellation tools, a hexagonal shape was chosen and applied throughout the surface of the model, counting 267 panels with double-curved outer and inner shell faces (Figure 4a). The panels near the base were significantly larger than the ones near the top, given the larger cross section and the dimensions of the prongs near the supporting area, while keeping the same grid and disposition of the panels. This further confirmed the necessity for a hybrid approach to fabrication. Average size was around 55cm in both direc-

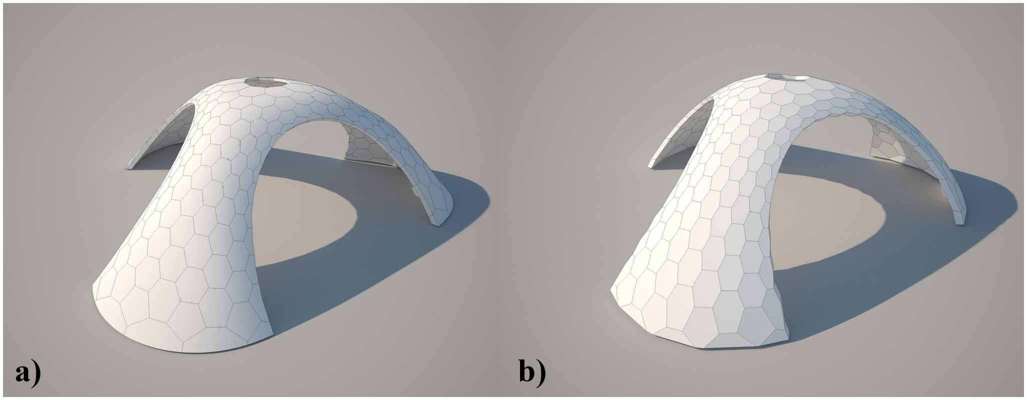


Figure 4
a) The tessellated structure with curved panel faces
b) The tessellated structure with planarized panel faces

tions of the boundary box, due to the size of model and the desired number of panels. Due to the changing Gaussian curvature throughout the model, a planar hotwire with a constant curvature was not an option as a cutting tool. Using a wire with a changing curvature, as was done prior (Rust et al, 2016a; Brander et al,2016a) was not an option due to lack of proper equipment.

In order to enable an easier fabrication process, a faceted panel appearance was chosen, making the front and back side of the hexagonal panels planar (Figure 4b). An add-on Kangaroo was chosen for aligning the six vertices of each panel into a single plane and generating a planar polyline, respectively. The structure still needed to have a certain thickness to overcome the load and forces acting on it. A custom script was generated offsetting the vertices of each hexagonal panel in reference to its surface normal vector. The offset vertices were joined into a planar polyline and lofted with the initial polyline to form the connecting faces of a panel, which are ruled surface. In such a manner, a planar straight hotwire could be applied.The load transfer would go perpendicular to the initial form, avoiding shearing. Once the initial and the offset polyline were used to form planar surfaces, they were joined with the ruled surface to form each panel respectively. Once the panels were generated, it was necessary to prepare them for the fabrication process.

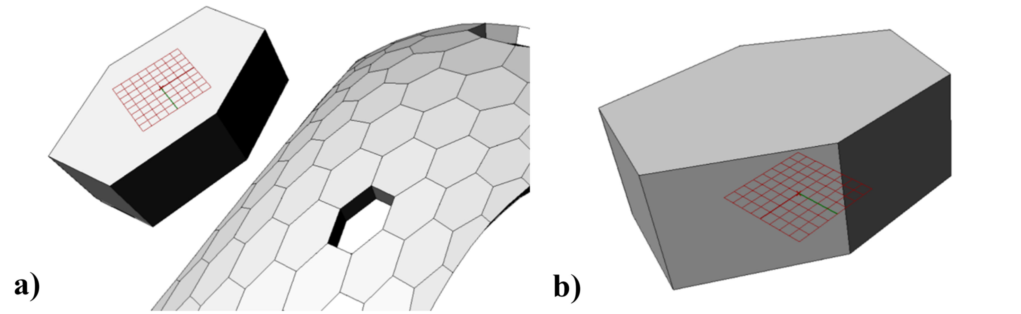


Figure 5
A coordinate system placed at the center of the planar hexagonal surface b) Orienting the panel in the world coordinate system

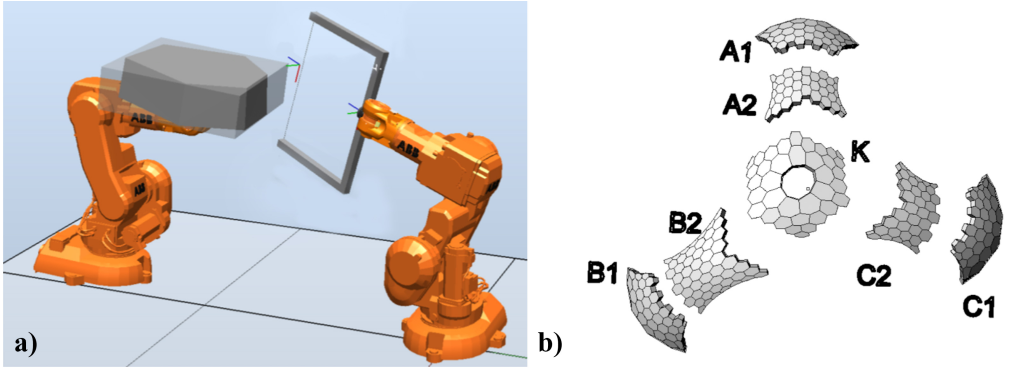


Figure 6
a) Positioning of the element with its bounding box on the 6th axis of the second robot b) Division of the structure into 7 parts for transportation and assembly purposes

## *THE FABRICATION, ASSEMBLY AND TRANSPORTATION PROCESS*

The fabrication process was done following a workflow done prior (Jovanovic et al, 2017). The only difference was that each panel had to be oriented in a certain manner, so its cutting path can be used later in RobotStudio for positioning purposes in both approaches. The orientation was done in two steps. First, a source coordinate system that lays in the offset planar surface of each panel was generated, with its origin placed in the center (Figure 5a). Second, the panel was oriented from its source coordinate system to the targeted world XY coordinate system and its origin (Figure 5b).The path was generated as was done in prior research.

Regarding the conjoined approach for fabricating the larger panels, the following methods were used. First, the calibration process is done in order to define the relative position of the robots to one another. A robot station for two robots was generated inside RobotStudio, using the acquired data. One larger panel was oriented in the coordinate system of the 6th axis of the second robot along with its bounding box (Figure 6a). The path was acquired by using the multimove feature that the software offers, and referencing the points and the orientation (robtargets) of the hotwire tool. The starting robtarget was placed along the edge of the bounding box, in order to be able to position the block during the actual fabrication process. The following robtargets were

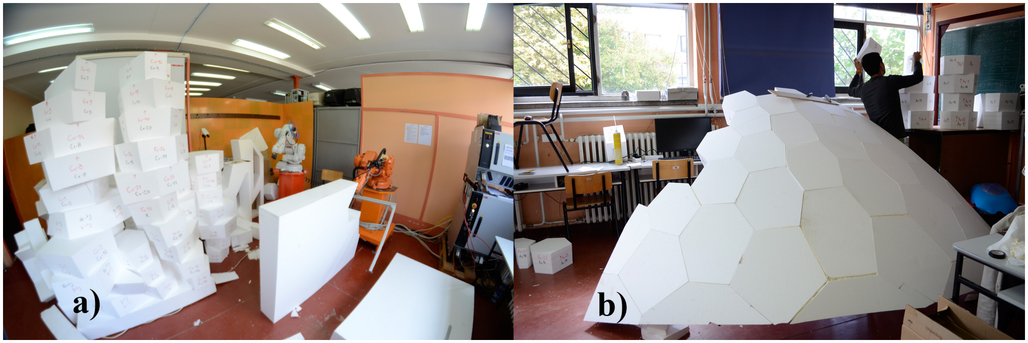


Figure 7
The depiction of the a) fabrication and b) assembly process being done in parallel

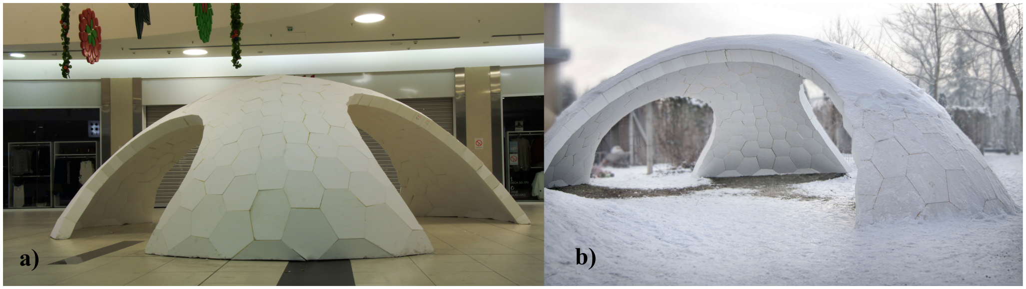


Figure 8
a)The finished structure on site during the manifestation b) the demounted and reassembled structure in the kindergarten backyard

referenced in the middle of the panel's ruled surface edges. The software generated the code for the robot controller, which was used for the fabrication process of larger panels. The assembly and transportation had to be taken into consideration in this process. The shell was divided into 3 prongs and a crown, out of which, every prong was divided into 2 more (Figure 6b).

Each of the 7 sections had around 35 to 40 panels, and the numbering was done accordingly. Since the assembly had to be done parallel to the fabrication process, due to relatively short time, it was not possible to use nesting algorithms for packing all the panels at once and waiting until all are fabricated . The panels had to be packed inside individual sections so they would take up as little space as possible from the 40 blocks measuring 1m x 1,2m x 0,2m that were obtained. The problem was that the length of the hotwire fork was only 60cm and the fabrication process had to be stopped and reengaged to adjust the block and the fork to avoid collision (Figure 7a). The running time of the process was 130 hours done during the course of 2 weeks. During the panel fabrication, the assembly process was under way, in order to allow for the panels to stick together better and due to scheduling (Figure 7b).

Keeping in mind the project requirements about assembly, the parts were assembled and transported to the manifestation site the prior night for putting everything together.

The assembly lasted throughout the night and the finished structure remained during the manifestation(Figure 8a). Afterwards, the structure had to be demounted . It was done by making a cut along the seams where the prongs connect to the crown part. Afterwards it was transported and assembled in the same manner, in a different location, a kindergarten, proving its demountability and easy transportation (Figure 8b).

## CONCLUSION

In this paper we presented a case specific approach to shell structure design and fabrication process adjusted to specific circumstances. The innovative approach to fabricating large scale panels was researched through conjoined parallel work of two industrial robots, where one robot was holding the piece, from which the other robot will cut out the desired shape using a hotwire tool. Following this workflow, similar structures can be fabricated, finding the best course of action when compromising between the general aesthetical appearance and desired design on one hand, project requirements and the available fabrication and digital tools. Compromising between the available resources and the optimal outcome, keeping in mind the integrated approach between all phases is necessary.

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