Safra Neuron Screen

Design and Fabrication

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Abstract

This paper provides an overview and an analysis of research in progress on automated facade pattern generation for The Edmond and Lily Safra Centre for Brain Sciences. This pattern is derived from accurate microscopic scans of brain tissue and is architecturally reconstructed with the implementation of structural and fabrication constraints. A single automated work-flow and pattern reconstruction is presented here.

Keywords:
cortical column reconstruction, parametric design, digital fabrication

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Figure 1. Visualisation of the completed neuron screen and building.

1. Background

A strong desire to accurately and iconically represent a building's function is often found in architecture. Such a desire faces the hardship of doing so, once considering architectural, structural, and manufacturing constraints. In this paper we introduce an automated work-flow that integrates these two criteria together to design, generate, and manufacture a neural facade pattern. The result of this work-flow is an architectural reconstruction of a section through brain tissue, specifically the visual neocortex area. This section, also known as cortical column, is scaled up to a full height of four floors and serves as the building's facade element.

Finding the right balance between the correct representation of original neuroscientific data and its architectural representation is facilitated by cooperation with the client itself, the Centre for Brain Sciences. Two main types of neurons are used to build the network, pyramidal cells with triangular shape and stellar cells with rounded shape. Pyramidal cells connect different layers within the cortical column by its apical dendrite (Fig. 5).

Currently built projects use different ways of rationalisation to allow for the fabrication of complicated patterns. Repetition of panels, such as Francis Soler's Ministere de la Culture et de la Communication in Paris, or incorporation of frames, such as Jakob + Macfarlane's Euronews headquarters in Lyon, are the most common solutions. Here we look at free-form, non-repetitive, frame-less panels.

1.1 The Safra Centre

The Edmond and Lily Safra Centre for Brain Sciences at The Hebrew University of Jerusalem is a pioneering research facility for the scientific exploration of the brain. Physically, the building (Fig. 1) acts as a gateway between the university campus and city - its dynamic social spaces and laboratory facilities are designed to attract exceptional scientists, as well as to foster an interest in the centre's research activities within the wider community.

The building is arranged as two parallel wings around a central courtyard. The upper levels house 28 highly flexible laboratories linked by social hubs, which are conceived to encourage interaction and the exchange of ideas between students and staff. The centre's progressive environmental strategy makes use of passive techniques to naturally reduce energy use.

Local materials, such as Jerusalem stone, are utilised where possible, and the building is orientated East-West to reduce solar gain. The upper three levels are shaded by a perforated aluminium screen, with a pattern derived from the neurological brain structure. Further passive cooling of the building is provided by translucent ETFE canopies to the West and East, which form distinctive markers for the main entrances.

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1.2 Design Objectives/Brief

The design objective is to generate a facade screen and shading element that iconically represents the Safra building's function. For this purpose a reference image which is identifiable and meaningful within the research community (Fig. 2 left) of Santiago Ramon y Cajal's drawing of a cortical column (y Cajal 1899, y Cajal 1928) from the beginning of 20th century is selected. This image was hand drawn by the scientist while observing brain tissue under a microscope and is an important image within the field of neuroscience. Using this image directly for a facade element raises many issues like difficulty of scaling up to building height, avoiding repetition when applied multiple times and difficulty to incorporate any manufacturing or architectural constraints.

To facilitate all of these aspects, a fully generated pattern representing a cortical column is proposed and designed (Fig. 2 right). This pattern shows the first five out of six layers of visual neocortex. Each layer is presented by a carefully selected type of neuron and placed so as to create a whole network of neurons.

2. Design Methodology

2.1 Neuron Library

The original neuroscientific scans of neurons are downloaded from www.neuromorpho.org (Ascoli 2006, Ascoli et al. 2007, neu). This webpage provides an open library of neurons. These are 3D computer reconstructions of microscopic scans of neurons sorted by brain area or author. The reconstructed format we use is a **.swc file*, which stores information as a text file and describes neurons like a 3D network of points (nodes) and their linear connections (edges) with given radii for each connection.

Additionally, each line has a tag about what kind of structure it is – apical dendrite (branches going to higher layers mainly receiving signals, basal dendrite (branches going to lower layers mainly receiving signals) or axon (branches sending out signals). Each node has an x,y,z coordinate, its own index and an index of a connected node.

All models used are from the primary visual cortex area of the neocortex of a rat, provided and reconstructed by Markram (Markram 2006). In total we use 70 unique files, each representing one neuron. These are grouped into types by layers.

2.2 Parametric Neuron Model

All neurons are first fully reconstructed in Grasshopper andRhinoceros (Fig. 3), the primary software used throughout the whole project. Raw data from downloaded files are parsed as a sequence of numbers that define locations of points in 3D

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space. Indices of connected nodes are reconstructed in the same way and are used to build an initial network of lines that represent centre-lines of dendrites. This is done in Python programming language and stored in a custom object class, which also stores a radius read in original raw data file for each of these lines.

To correctly reduce the number of branches in the final pattern, a sub-section of the neuron is created. The depth of this section is a variable that trims off any branches that are outside this range.

Five key steps (Fig. 4) is used to simplify the centrelines and build surfaces. The pseudo-code (implemented in Python) for neuron generation is described by Algorithm 1.

Algorithm 1 Neuron generation

```
while next branch in neuron available do
    rebuild center polylines by connecting nodes as points from the raw
    data
    if distance of this point not close to existing point then
        skip
    end if
    store points as a list in a neuron class
    sample these polylines
    interpolate these points to smooth the centreline
    sort these curves by their length and distance from the origin of the
    neuron
    count number of branches
    if length or distance > target value then
        skip curve
    end if
end while
```

2.3 Constraining Parametric Model

Incorporating some of the structural and manufacturing constraints is necessary and most efficient on the level of centre-lines. To allow all spigot locations to be on a given grid or within predefined zones, which is discussed later, all these centre-lines have to go through specified points, representing a possible spigot location. Another advantage of introducing these fixed points is that more branches intersect at those locations, thus minimising the number of free branches which structurally act as cantilevers and thus have limited performance. A Python function rebuilds the centre-lines and forces them to go through these fixed points. Only a small maximum movement is allowed to keep the original visual characteristics of branches. Each fixed point finds a point closest on a centre-line, and if within given tolerance, the centre-line is split into two halves, shortened and the newly created gap is replaced by a new curve that goes through the fixed

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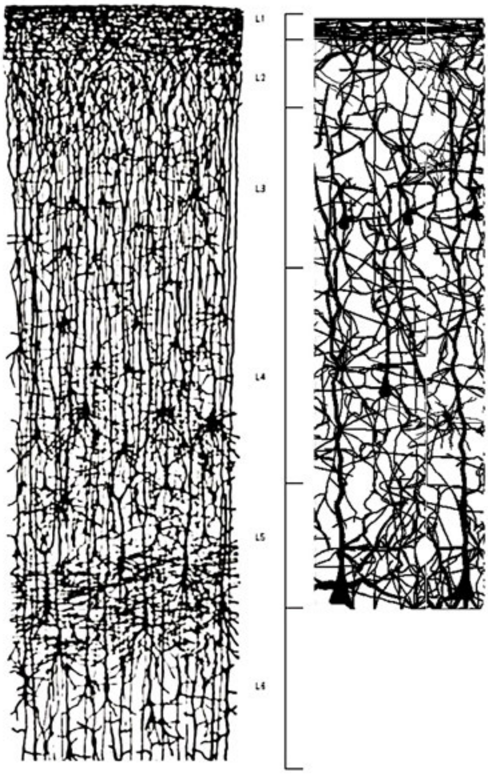

Figure 2. Vertical alignment of the facade screen (right) with Ramon y Cajal's drawing (left) of cortical column showing generated target layers.

Figure 3. All 70 reconstructed neurons used to generate the pattern.

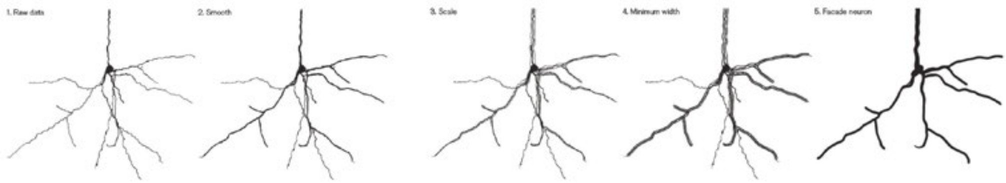

Figure 4. Five key steps in the process of simplifying and smoothing the raw data.

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point and is tangent to the two parts of the original centre-line. The new three curves are joined and rebuilt into a new single centre-line.

Three main groups of fixed points are introduced because of required manufacturing and structural constraints. Each panel is attached by spigots on its vertical edges, top and bottom horizontal edges and a single point in the centre of the panel.

Once the selection and modification of centre-lines is finished, these are offset to create surfaces. The amount of offset is primarily driven by the original radius from the raw data. Because each branch has to have a minimum thickness to work well structurally and another minimum thickness to hide a connection detail on the back side of each panel, the original raw radius is first scaled up by a fixed number. Scaling all radii by the same number keeps the characteristic tapering of dendrites. Fixed number scaling also keeps the characteristic average thickness of branches that varies between neurons in different layers – neurons in lower layers tend to be thicker and larger compared to neurons in higher layers. To minimize noise in the raw data, this tapering is further forced by a function that checks for a gradient along the centre-line. Each centre-line is sampled to a dense list of points; each point is then offset along a normal vector to both sides to a distance driven by the radius of the closest raw line. A list of points on either side is generated and an interpolated curve created from those points.

These two offset curves define edges of a loft B-spline surface of degree 3, which creates the actual fill of branches. Additional surfaces at the end of each centre-line creates a smooth ending filet. This end surface is generated from a curve that is tangent to the two offset curves and goes through a point on a prolonged original centre-line to create a tip of the branch.

2.4 Generating Somas – The Cell Bodies

As somas are not described by enough points in the raw data file and at the same time have a shape crucially characterising each neuron type, they are drawn manually for each of the 70 neuron files. There are two main shapes of somas: a circular one for interneurons and a triangular one for pyramidal cells. Further somas are significantly larger in lower layers then in higher layers, e.g. somas of large pyramidal cells in layer 5 have larger somas than small pyramidal cells in layers 3 and 4. These manually drawn templates of somas are then positioned to the centre-point of neurons within the pattern and a small noise is applied to remove any repetition when the same neuron is used more than once. This noise is generated by scaling the soma by a small random number different in x and y directions and in a plane that is rotated by a small random angle to introduce skewing.

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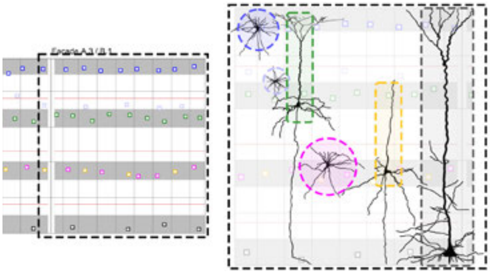

Figure 5. Centre-points of neurons, e.g. soma's locations, placed within the solid areas of facade. Colours represents different neuron types with a typical sample shown to the right. Neurons with circular marker represent interneurons (stellar cells) in different layers, rectangles represent pyramidal cells.

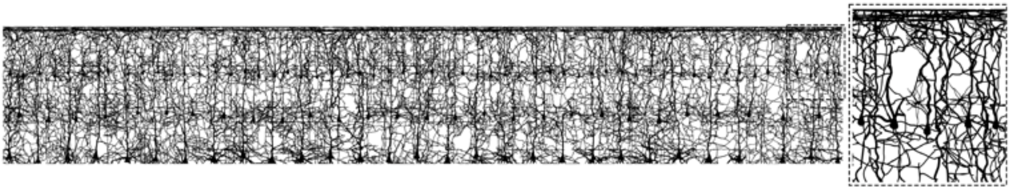

Figure 6. Visualisation of the pattern itself showing three facades connected together into a single pattern. Few panels shown with larger scale to the right.

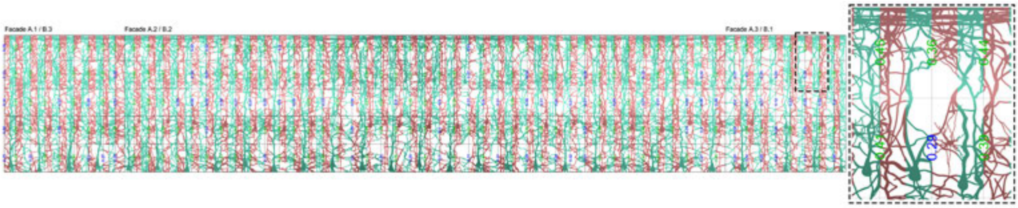

Figure 7. Added solidity of two halves of panels attached to an adjacent vertical mullion determines the number of spigots along that mullion. Few panels shown with larger scale to the right.

Figure 8. All 290 panels shown in different colours. Few panels shown with larger scale to the right.

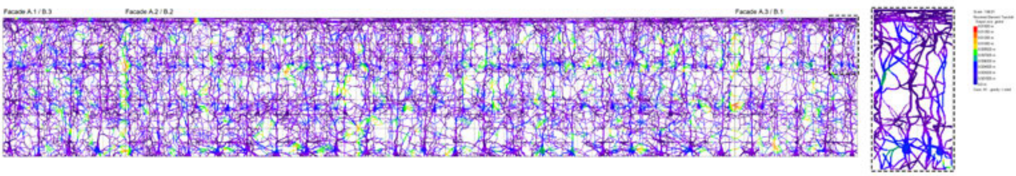

Figure 9. Structural analysis of all 290 panels analysing combined dead load and wind load. Few panels shown with larger scale to the right.

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2.5 Layer Mapping and Neuron Size

Another key characteristic of pyramidal cells is what layers within the cortical column they connect by their apical dendrites. Pyramidal cells in layer 3 are connected to layer 1, pyramidal cells in layer 4 are connected to layer 3 and large pyramidal cells in layer 5 are connected to layer 1. Although the raw data puts neurons to the correct layer and gives it the right size to connect to the correct layer, as the generated screen pattern has the cortical column layers aligned with building's floor levels, a small modification needs to be done to match the distance of correct connecting layers. This is simply done by scaling the neurons along its centre-point by a ratio that is calculated as a ratio between the height of a bounding box of all apical dendrites within a neuron and the target height given by a distance between connecting floor levels.

2.6 Horizontal Branches in Cortical Layer 1

The very top layer 1 is filled by separate horizontal branches, which are directly generated by a Python script and connects random points within allowed vertical zones for spigot locations along the vertical mullions. These points define centre-lines that are offset by a fixed number to create two edges of resulting surfaces.

2.7 Network

Neurons in the neocortex are of multiple different types. The type defines its shape, size, and connectivity to other neurons and other layers. The cortical column is made of 6 layers. Our pattern rebuilds five of them, leaving out layer 6. As each neuron has two key parts – the soma (central nucleus) and dendrites and axon (branches) – and the facade's objective is to keep all parts of the pattern within a standing or sitting person's field of view more open (less dense), we deliberately place somas into areas in front of solid parts of facade. Because these are mainly floor and ceiling constructions and we cover three floors, we have in total four separate height levels for placing somas (and thus neurons). These height levels drive positions of neurons in levels 2, 3, 4, and 5. Layer 1 is made by thin horizontal branches and thus is put jointly above layer 2 on the very top floor of the building.

For structural reasons somas are placed close to potential structural supports, because somas are a large solid piece and so the heaviest part from a structural point of view. This is considered when generating the initial grid of points based on a structural grid of possible support locations. These are defined by the window mullions behind the pattern. A centre-point of each neuron is then generated as a random offset from this structural point within a predefined range along x

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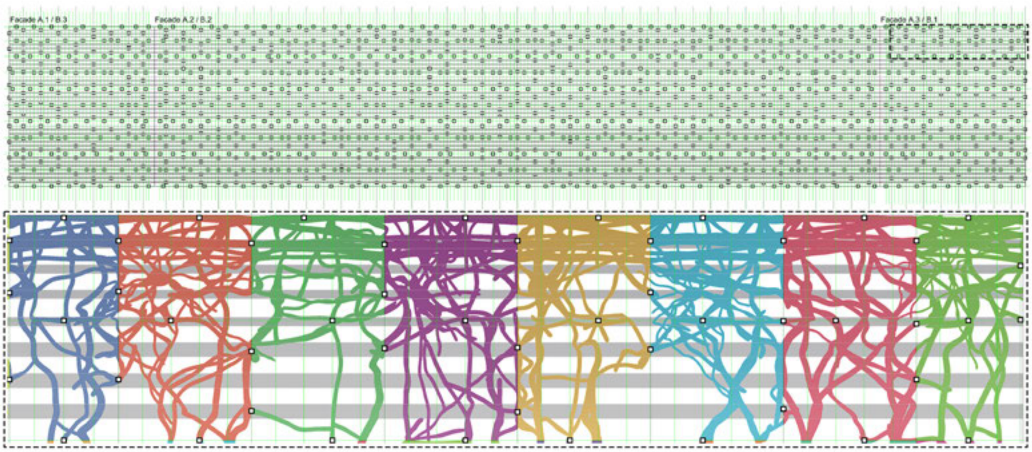

Figure 10. Location of all spigots overlaid with corresponding vertical grid and horizontal target zones required for spigot placement.

and y axes (y axis is z axis in the building's coordinate system). At the same time these centre-points are constrained to the facade's solid areas only for transparency reasons (Fig. 5). Only small stellar cells in layer 2 with thin branches and small somas are placed off the solid zone.

The y coordinate of each centre-point then defines the layer within the cortical column and thus the type of neuron used in that location. For layer 2 (the very top floor / roof level of the building) a random selection among 20 neurons is made. 50% of those neurons are small Basket cells and the other 50% are small Martinotti cells. Both are sub-types of inter-neurons, which are neurons characterised by rounded shape of soma and missing the apical dendrite, the thicker vertical branch coming out of soma.

Layer 3 (second floor level from the top) is made of neurons selected from 20 different small pyramidal cells. Pyramidal cells in this layer are characterised by smaller somas of triangular shape and thicker vertical branch (apical dendrite) connecting this neuron to layer 1.

Layer 4 (third floor level from the top) is made of combination of inter-neurons and pyramidal cells. Both neurons in this layer have larger somas compared to previous layers. We use 50% of each type, so there is always one pyramidal cells followed by one inter-neuron. Inter-neurons are further selected from a group of Martinotti and Basket cells. Pyramidal cells in layer 3 are connected to layer 2 by apical dendrites, so the cell is forced to be the correct height.

Layer 5 (the very bottom floor level in the building) is made of large pyramidal cells only. Because the density of neurons in layer 5 is smaller, we place cells only to every other structural point, leaving more space in between. We have 10

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different pyramidal cells to choose from and they are forced to be the correct height to connect to layer 1.

Layer 1 is generated separately as a number of thin horizontal branches spanning over the whole width of the building. They are placed above layer 2 cells and also create a solid visual ending of the pattern at the top edge.

After initial generation of centre-points (Fig. 5) of cells and assigning a type of corresponding neuron, random rotation of each neuron is applied. This rotation is along the z axis of the neuron and provides further diversity in the pattern when the same neuron is used more than once – on average each neuron is used three times to reach the total number of 230 neurons. This rotation is within plus-minus 10 degrees additionally to 180 degrees used for mirroring. Somas are generated separately as discussed in previous sections.

The final network (Fig. 6), which is generated in original dimensions and is 900 nm in height, is scaled up to 14093 mm to match the facade's height. This gives a scale of 15659:1.

2.8 Workshop

To facilitate the search for the right balance between architectural representation and accuracy, we collaborated with the client directly, which is the Centre for Neuroscience. We held two separate workshops with the leading neuroscientist to discuss and develop the logic behind the pattern.

During these workshops (Fig. 11), it proved to be very useful to have a parametric model of the work in progress pattern and do live changes to the pattern. We developed a pseudo-code for further development that resulted in the algorithm described here. Having a descriptive rather than prescriptive understanding of the logic of the pattern helped to find flexible areas in both fields and intersect them.

2.9 Fabrication

All panels will be water jet cut from 1500 mm x 3000 mm sheets of 12 mm thick aluminium.

The overall pattern goes around the whole building but is split into two identical halves. This makes it easier to manufacture by reducing the number of unique panels to half, but cannot be seen anywhere on the building, because one half is rotated 180 degrees relative to the other.

In total there are 600 glass panels. Every two of these are covered by one aluminium panel of double size, which gives 290 unique aluminium panels (Fig. 8).

Each aluminium panel is attached by a number of steel spigots. These spigots are attached to the glass mullions and transoms behind. Spigots on vertical mullions transfer dead load as well as wind load. Spigots attached to the horizontal transom take only wind load.

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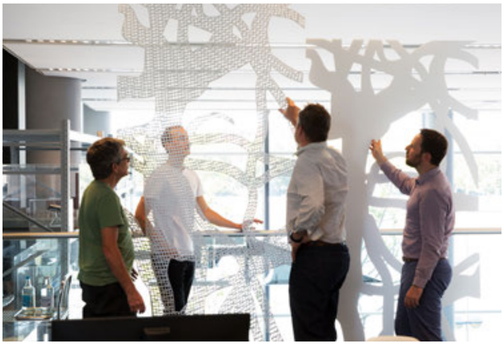

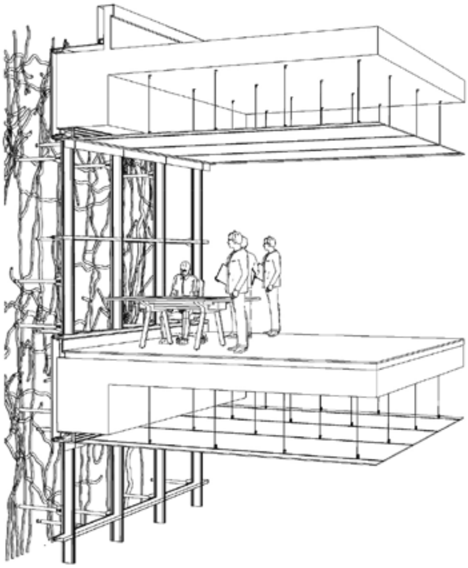

(from left to right and top to bottom)

Figure 11. Design and process review workshop with client, neuroscientist, and fabricator.

Figure 12. Section of facade and interior.

Figure 13. Scaled foamboard mock-up of the full screen.

Figure 14. Scaled 3D printed model of a portion of the screen reconstructed in 3D before flattening.

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A key constraint is to achieve a total optimal number of spigots carrying the whole pattern. This divided by the number of panels gives an average number of 4.8 spigots per panel. As all spigots on the outer border carry two adjacent panels, while only one spigot in the centre of a panel carries only itself, the average number is 8.8 spigots per panel. The pseudo-code for placement of spigots on vertical edges is described by Algorithm 2.

Algorithm 2 Placement of spigots on vertical edges

```
Require: solidity for each vertical edge as a sum of two halves of adjacent
  panels (Figure 7)
Ensure: solidity of all edges < 0.5
  while next panel edge available do
    if solidity of this edge < 0.33 then
      assign spigot at 1/3 of the edge length
      assign spigot at 2/3 of the edge length
    else
      assign spigot at 1/5 of the edge length
      assign spigot at 1/2 of the edge length
      assign spigot at 4/5 of the edge length
    end if
    find closest point from these points on any center-line → output actual
    spigot location
  end while
```

For additional strength against wind load, one spigot is positioned on the top, one on the bottom edge, and one on a horizontal line going through the centre point of each panel. The initial rule of placing the spigot to the widest branch is replaced by a spigot closest to the midpoint of the edge, which gives best structural performance. All of those spigots are localised in one of the four possible locations on a transom. This allows the transoms to have only four different types and is therefore cheaper to manufacture.

Because centre-lines are already forced to go through the zones allowed for spigot placement, the closest point on them is also within those zones (Fig. 10).

To simplify installation of the panels and to ensure that each panel is supported by at least three points not on line, each panel must be made of a single piece. This is achieved by having the pattern dense enough, which is controlled by the parameter number of branches. This parameter is different for each of the neuron types, so slightly different densities within the pattern are achieved. Additionally, if there are still any small pieces left, an algorithm removes them completely.

It was calculated that a maximum length of any cantilever must be less than 500 mm. This is controlled by a Python function that splits all centre-lines against all other centre-lines, and if any of the end pieces is more than 500 mm, it shortens it to 500 mm minus a small additional random number to avoid a regular look.

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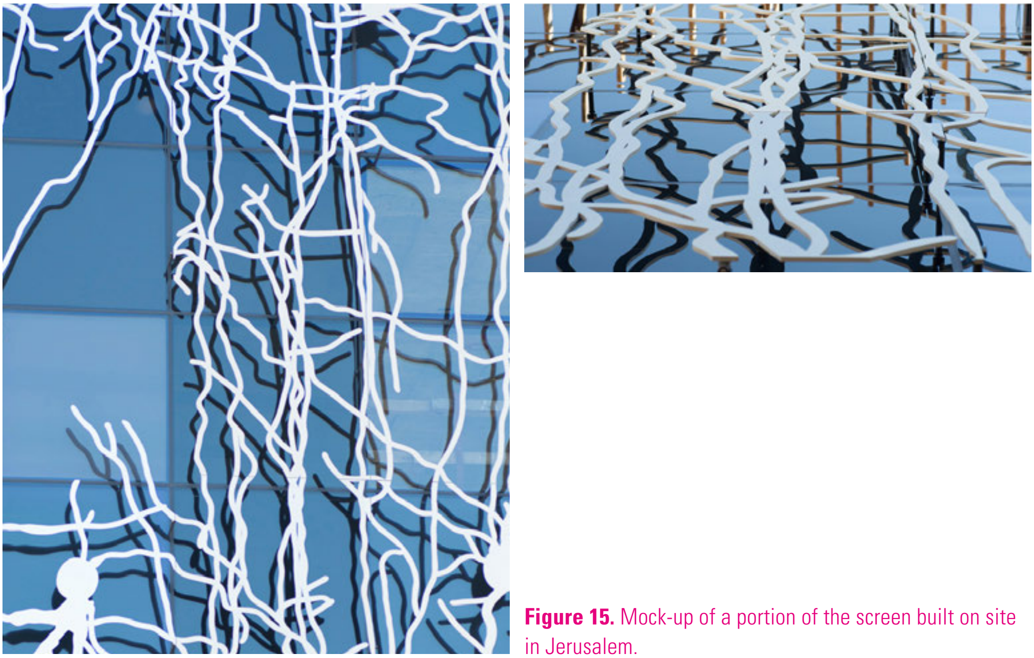

Figure 15. Mock-up of a portion of the screen built on site in Jerusalem.

A structural analysis of all 290 panels was done (Fig. 9) in General Structural Analysis (GSA). An automated link from Grasshopper creates a GSA file that is then analysed and gives information about overall displacement. Having this as a Grasshopper component allows us to easily define locations of different supports. Spigots on vertical edges work as pins fixed in x, y, and z directions. Spigots on horizontal transoms are fixed only in x and y direction, thus not taking any dead load. Further settings for the analysis are 12 mm thick aluminium and 1430 Pa wind load on each face, which is the highest wind in Jerusalem.

The analysis itself is mesh based. For this each panel that is drawn as a B-spline surface so far has to be meshed and the mesh needs to be as regular as possible. This is again done automatically in Grasshopper as well as finding the support location as a closest point on the mesh from a spigot location.

To achieve the target maximum deflection of 15 mm, multiple full cycles of geometry generation, panelisation, and analysis had to be done. The interim results and careful observation redefined the rules for spigot placement and overall density as discussed before. This made around 95% of the panels perform well.

To effectively fix the last few percent of panels as well as to incorporate and visually integrate openings for the escape windows, which are 12 windows that need to be completely clear, manual modifications of the generated surfaces were necessary. All surfaces are baked into Rhino, modified, and then loaded back into Grasshopper, panelisation and analysis is automated again.

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3. Physical Prototypes

Multiple methods were used for evaluation of the aesthetic and structural properties of the pattern.

3.1 Foam-Board Zund Cuts

A scaled full-facade model was done from a foam board and cut on a Zund machine (Fig. 13), which allowed us to quickly and cheaply create 1:1 pattern prototype. The whole facade was split into 10 boards of size 1200 mm x 2400 mm. This was used to evaluate the overall density, complexity and correctness of the pattern (Fig. 13).

3D Prints

Because the very initial raw data are 3-dimensional, few experiments were done to visualize the pattern in 3D (Fig.14). This is the same pattern as the facade pattern before applying any manufacturing or structural rules. A sample of such structure was 3D printed on an SLS machine (Fig. 14).

Mock-up

A full scale mock-up of multiple glass and aluminium panels was done on site in Jerusalem (Fig. 15). This shows the final detailing and surface treatment.

4. Discussion

The ability to have a smooth work-flow including a structural analysis and automatic processing of raw scientific data allows content accuracy to be implemented and aligned with manufacturing and architectural constraints.

The overall size of the final pattern is 86,313 mm (width) x 14,093 mm (height). As the height of the pattern would be 900 nm, that gives a scale of 15,659:1. Minimal solidity of the panels is 10%, average 36% and maximum solidity 61%. 41% of all vertical edges have two spigots, 59% have three spigots. The total number of spigots is 1,403 per half, 2,806 in total. The number of neurons used to generate the full pattern is 207, based on 70 unique raw files.

The pattern is designed so it performs well for 1,430 Pa wind load and 15 mm maximum deflection, fabricated from 12 mm aluminium panels. The minimum width for unsupported branches is 38 mm, otherwise 49 mm. The initial pattern before implementing the manufacturing constraints has 8320 branches with 39,749 intersections and would need 7,216 spigots. This was reduced after geometry modifications by 63% to 2,685 spigots. And this was reduced further by 48% after careful spigot location selection to 1,403 spigots.

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The overall process could be further optimised by having a two-way closed loop with GSA. In this case the initial strategy was good enough to handle around 95% of panels.

As the project developed in complexity, more consultants got involved, and deadlines approached, the usefulness of the digital workflow became obvious and allowed for rapid changes to the design; this meant it was necessary to keep the model up to date right through to fabrication.

5. Conclusion

The digital and practical work-flows presented here proved to be relatively productive for multiple design and construction criteria to be integrated into a single work-flow. It allowed a pattern derived from accurate microscopic scans of brain tissue to be generated and architecturally reconstructed with integration of structural and manufacturing constraints.

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