

Subdivision Surface Modeling to Foster Responsive Design Solutions in an Integrated Multi-disciplinary Team

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This paper documents an architectural project developed using subdivision surface modelling. Subdivision surfaces are not new, and the tools are readily available in many 3d modelling applications. Despite their age and availability and recognised benefits they are rarely applied in architectural projects furthermore there is paucity of published case studies that demonstrate these tools in action. The second contribution to the field that this paper offers is in recognising the way in which subdivision surfaces can provide a new form of collaboration. Our core team consisted of architect, artist and 3d modeller and the project was inspired by a ceramic sculpture with unusual geometry. Subdivision surface modelling enabled a unique form of design exploration, feedback and communication between people with diverse skills. This case study therefore offers both insight into applied use of subdivision modelling and further depth into the way it enables interdisciplinary collaboration.

Keywords: *Subdivision surface modelling, Ceramic sculptures, Multi-disciplinary, 3D scanning*

INTRODUCTION

In this paper we describe a multi-disciplinary design workflow where subdivision surface modelling (SSM) was used to develop a building proposal for an architectural competition (figure 1). Our aim is to document the application of SSM itself and to demonstrate how this method of modelling provides the possibility of integrating a diverse design team. The background to the geometry used for the competition and the form of the design team is therefore par-

ticularly important.

The formal inspiration for this proposal originated in a handmade sculpture made by a ceramic artist. This sculptural object, if scaled up to the size of a building, it could serve as a rich conceptual basis for a competition entry, where an open ground floor could serve as a public plaza. The ceramic form not only captured an intent to maintain the ground plane as an open public space, it also indicated how the building could be resolved structurally and pro-

vided a compelling topological and logical organisation for the internal building program. Subsequently an initial design team was formed consisting of architect and artist.

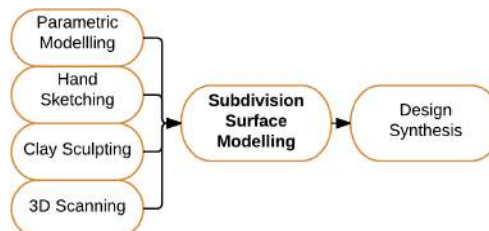


While the sculpture provided abundant ideas for the architectural premise of the competition proposal it also presented some complex problems in terms of geometric representation. As a result the project team grew to three, from architect and artist to include 3d modeller. From the outset it was clear that in order to function well as a building the original geometry would require several iterations of geometric modifications as the design developed. The unusual topology of the form included several branching junctions which are particularly difficult to model using traditional computer modelling techniques which tend towards methods that involve linking and deforming of rectangular or sheet like elements. We accurately captured the form in an electronic format using a 3d scanner. 3d models produced by 3d scanners are representations that usually consist of hundreds of thousands of vertices and thousands of faces which can be edited to make local geometrical changes, but do not really suggest a logical method for control and modification of global geometry.

SSM offered a unique approach the resulting surfaces are defined by recursively refining an initial polygonal mesh. We could define our models with simple geometry with the minimal of control points and yet we could elegantly geometrically represent the branching forms that were an essential part the original sculpture. Theoretically a limit surface can

be generated by infinite recursion. This is usually impractical in architecture and stopping the refinement when the mesh size represents a facade system or structural grid is more convenient. One of the published benefits of this aspect of SSM is that the coarse mesh can be used early in design to undertake fast analysis that can drive the design in more efficient directions. For our competition stage goals were to match the original sculpture while also providing geometry that could function architecturally. The initial coarse mesh could be easily controlled within a modelling application by the 3d modeller while the artist and the architect could review the refined mesh and provide instructions for further manipulations to achieve aesthetic and architectural criteria.

Working with this rational method we realized that this technique was enhancing our ability to collaborate as a team providing a rapid feedback mechanism that enabled us to directly discuss the interrelationships between architectural requirements, geometric manipulations and the impact on the artistic and aesthetic qualities. It facilitated a hybrid method of working where hand sketching, clay sculpting, 3d scanning and parametric modelling could inform each other on an equal basis (figure 2). Using SSM in this way we created a computational parallel that was analogous to sculpting with clay, this straddled physical and digital modelling domains and subsequently facilitated a new means of real time communication across a design team with a diverse range of skills and experience.



We established the building geometry directly from the original mesh and all systems and subsystems within the building could be directly derived by care-

Figure 1
Competition entry image demonstrating the unique urban response generated from the team's integrated form-finding experimentation process

Figure 2
SSM as an integrator of disparate tools, mediating between physical and digital techniques

ful control of offsets and the iteration of mesh refinement. The SSM approach and the geometrical hierarchy that we had established provided a novel information modelling system. As the project developed and we moved towards production of a set of drawing and images for the competition entry we could extract 3D data that related directly to the structural and architectural information domains simply by adjusting the offset and iteration parameters.

SCULPTURAL FORMS

The ceramic sculpture that inspired the competition design was originally conceived as one of many components for a matrix that was based on the structure of a root system that would be tasked with additional aesthetic rules. Plant roots are fibrous threads seeking pathways in a complex matrix of dense and less dense soil mass. The clay model predicts a knot born of interacting pressures. The artist's interest in the arabesque figure would form the aesthetic rules that were applied to the root form. The cursive vocabulary of the root is metamorphosed with the constructed cursive text of Islamic writing. Calligraphy, or khatt in Arabic, originates from 'line', 'design', or 'construction'. For Islamic visuality, the arabesque is the transcendental metaphor of cursive space.

The objective of designing a component that would align with a variety of other similar but different knots, led to the grammar of the knot-root. The concept for a matrix of root-knots was a question of three-dimensional patterning in three-dimensional space. To imagine a space-filling pattern led to the conclusion that each knot-root needed multiple branches that would reach out in global directions (and like a root, gravity is ignored). The branches needed to be clipped short, otherwise connecting to neighbouring components would be unmanageable. Given that the original matrix was amassed of non-mathematical forms, a final element, a flexible connecting tissue, such as plastic or polymer tubing, was needed to enable the connection of rigid forms that frequently did not perfectly align.

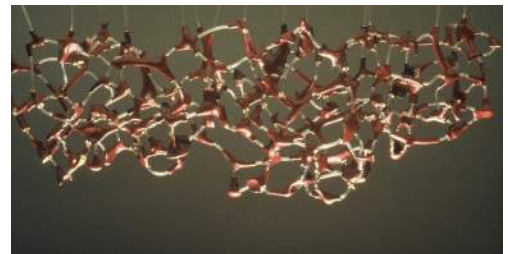
The matrix sculptures are the combined results

of many smaller methodological studies which involved the development of a set of ceramic components which captured possible junction forms of two, three, four and five branches and sometimes also the morphology of stubs. Each part played a role of varying importance in the creation of the matrix ceramic sculptures as an individual syntactic or grammatical structure. In the sculpture that inspired the library design a series of these components were joined in a raw clay form. The individual parts were made by pressing clay into moulds and then unifying them in a continuous whole. This approach using the raw material allowed additional clay to be added at the joins which permitted various smaller modifications to be made letting them to be combined and to further extend the language of the overall form. Once the final form was reached, the piece was glazed and fired (figure 3). The matrix sculpture shown in figure 4 is built by assembling several hundred of these parts which have been glazed and fired and connected them with plastic tubing.

Figure 3
Glazed ceramic sculpture that inspired the library design.



Figure 4
Matrix ceramic sculpture by Neil Forrest



INITIAL DESIGN MOVES

The brief Daegu Gosan Public Library called for a 3100msq contemporary library on an urban site in Daegu, South Korea. The project began with the idea of a building as a continuous space and a free ground plane that would preserve the site's existing green space. This intention to create a building that would behave spatially and formally to preserve the existing natural diversity of the site lead to the search for a language that could accomplish this, spatially, structurally, and tectonically. The branching shells which the artist Neil Forrest was exploring in his work was a clear starting point. His work was exploring continuity of space and form in the branching structures in roots, tree branches and coral reefs and then abstracting and appropriating those elements to create an expandable vocabulary. The branching form of the ceramic sculpture was an opportunity for a dynamic and expressive structure dispersed in three dimensions across the site, which opened up the ground plane, and allowed for a series of galleries above ground level. These forms offered continuous spatial sequences inside them, and a spanning capability in which the curving forms of the branched structures could be lifted above the ground in a dispersed set of galleries. The resulting form inspired explorations into the construction of ship and airplane hulls, and how they perform structurally. (Figure 5)



MODELLING PROCESS

Subdivision Surfaces

Subdivision surface modelling has been well used for character modelling in the games and in computer animated films (Zorin et al 2000), however despite several published benefits in building construction (Shepherd and Richens 2010, 2012, Shepherd 2014) and the availability of SSM within standard 3d modelling applications the use of this method in architecture is uncommon. Our experience of applying SSM methods demonstrates directly the potential benefits and highlights specifically how SSM can offer a close to real time method for communication and analysis of potential designs.

SSM uses a network of polygons to describe a smooth surface. To generate the smooth surface the network of polygons is iteratively subdivided, new vertices are defined and connected as new polygons within a network. Several different subdivision schemes exist for adding, averaging and sometimes removing vertices based on the location of the original vertices and the preceding generation. Eventually a smooth limit surface can be reached. The subdivision process can be stopped before reaching the limit surface resulting in a faceted polygon mesh but one that is smoother than the original polygon network.

In character animation the level of subdivision is controlled by proximity to the camera. As objects get closer the levels of subdivision are greater meaning more polygons and a smoother surface. Further from the camera less detail is required and therefore fewer polygons are generated saving processing power. In architecture this procedure has a parallel. Later in the design process more detail is needed but in early design stages less detail is beneficial. A coarse polygon network representing a building is useful because polygon analysis such as incident solar radiation, structural performance, acoustic performance or shadow studies can be done close to real time. The results are good enough to make important early design decisions. The original control network is easy to change so multiple options can be studied both

Figure 5
Concept sketch by
Richard Kroeker

quantitatively and the qualitatively. Ultimately in architecture the limit surface is not required as the level of subdivision can be set to correspond to discrete polygons that represent facade panels or a structural grid.

Despite the potential benefits of using SSM they have been under explored, it is more common to use B-spline or NURBS surfaces to describe architecture with curvilinear geometry. These methods present two difficulties. First these surfaces must be post-rationalized to produce a panelisation strategy that can be used for construction. Second, using B-spline and NURBS is equivalent to using a rectangular sheet or several linked sheets to describe a shape, making it very difficult to describe complex forms or surfaces that include branching with these techniques.

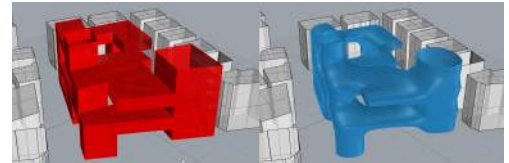
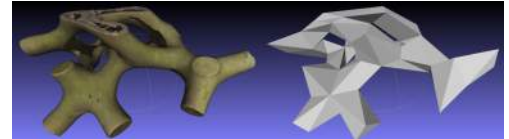
Methodology

In our process it was clear that a NURBS based method would be difficult to control and would not produce the desired aesthetic qualities. SSM was chosen primarily as a means to represent and control the branching geometry of the original sculpture. The ability to shift between coarse and refined mesh results by controlling the number of iterations permitted us to optimise the aesthetic and architectural goals using visual assessment by both the artist and the architect.

The first step in working with the ceramic form was to scan the entire sculpture using Dalhousie University Libraries NextEngine 3D scanner services (Groenendyk and Gallant 2013). The scanned models consisted of around 277000 vertices and 554000 faces which was too complex to form a basis for manual 3D editing. Quadratic edge collapse decimation [1] is a tool that reduces the count of polygons in a mesh. Experiments with this algorithm in the free software MESHlab [2] resulted in loss of the original form and yet still too much complexity to permit any manual control (figure 6).

An initial investigation of subdivisions surfaces began with an attempt to rebuild the full ceramic model using a very coarse mesh network modelled

on site. The model was then subdivided using the Weaverbird plugin [3] in the visual programming interface grasshopper [4] within the Rhinoceros 3d modelling application [5]. While the results of this (figure 7) were not acceptable for our design process, this experiment offered some valuable insight into the design possibilities of having parameterized control of the refinement of coarse mesh and the ability to easily offset the resulting subdivided mesh.



The dissatisfaction with these initial experiments led us to return to the original sculpture that inspired the design and we sought a deeper understanding of how conceptually and physically this work had emerged. We believed that if we could understand the syntactical structure of the ceramic form, we would be able to develop a corresponding process with the computer model and harness the physical form as mutable. The experiments also made the team realise that we wanted fidelity to original form and our combined understanding of how this was achieved was essential. We needed to develop an understanding and method similar to the modelling of the ceramic branching components that the artist had developed for his matrix sculptures. Once we had the ability to model and control the parts we could begin to combine them and adjust them to model the complete sculpture.

The artist located 10 of the original, fired but unglazed, component parts in his studio that he believed may have been used in combination to define

Figure 6
Original scanned
model (left) and
after decimation to
200 faces (right)

Figure 7
Coarse mesh
network (left) and
subdivided result
(right)

the sculpture. While waiting for 3d scans (figure 8) of all these parts we undertook some simple modelling tests to anticipate the forthcoming workflow. These test proved very promising (figure 9) and suggested that our instincts that paralleling the physical sculpting process with the computer was the key to capture and control of the ceramic geometry.

Once we had the parts scanned, the team used MeshLab and quadratic edge collapse decimation to reduce these meshes from 100000 vertices and 150000 faces to around a 1000 vertices and 2000 faces. This made opening and viewing the model in Rhinoceros 3D relatively quicker, but also preserved the original form so that we could reference it and match it with the subdivision version.

Sitting in front of a screen artist and 3d modeller examined each part scan in detail. Of the original ten parts four were identified as being potentially used in the sculpture. We discussed what we each found compelling about the nominated clay form. We agreed there were obvious rules about how the branches intertwined, that there was no single point of origin in the branch, that there was a gentle swelling of the branch if it were to merge with another, and understood the branches tapered as they moved away from the perceived centre. Proceeding in this way we combined the modelling steps required to produce a controllable subdivided mesh with the memory of the aesthetics and process of the physical sculpting process. The basic topology of each component was identified and modeled with a coarse mesh of around 150 vertices and 30 faces. The faces and vertices of the coarse mesh were iteratively manipulated in small groups and the resulting subdivided mesh compared to the scan until a satisfactory result emerged (figure 10). We repeated this approach for each of the 4 component parts and developed a further modified component based on the original (figure 11).



Figure 8
Ceramic
component

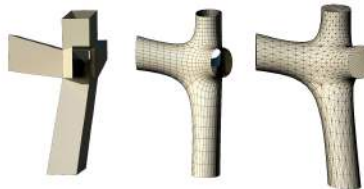


Figure 9
Initial modelling
test simulating the
form of the ceramic
parts

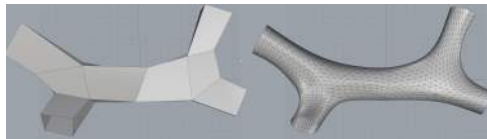


Figure 10
Matched mesh
topology network
(left) and refined
mesh (right)

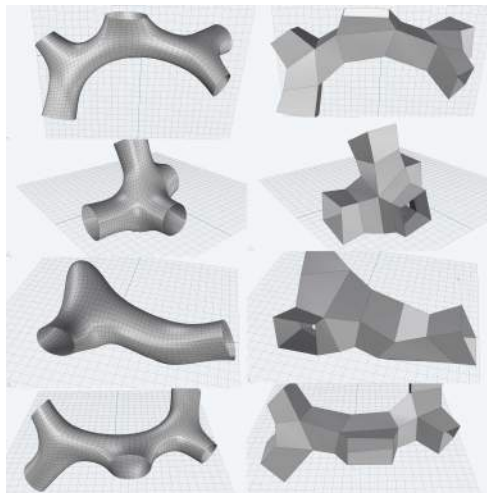


Figure 11
Computer models
of the components.
Refined meshes
(left) and coarse
meshes (right)

Figure 12
Sequence of steps
to combine parts,
adapt and match
the original form

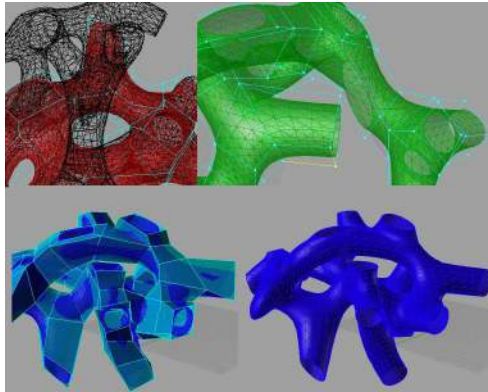


Figure 13
Sketches, ceramic
models, 3d printed
models and the
computer were
integrated using
subdivision surface
modelling

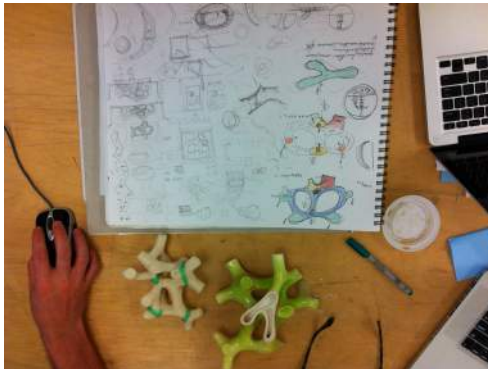
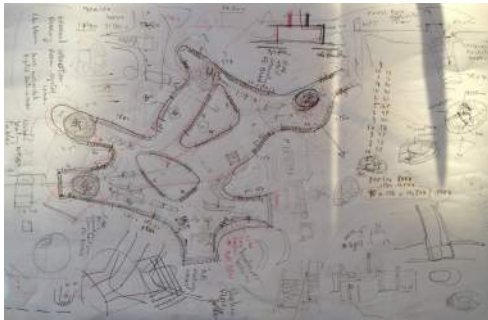


Figure 14
Architect's working
sketch during form
rationalisation



Working through this part of the modelling process we began to realise that something unique was occurring facilitated by SSM. A link was being formed between two collaborators with very different experiences and skills. 3d modeller and artist sat side by

side with the original ceramic parts on the table and with laptop and mouse gradually informing one another of the considerations each was making or had made with their respective modelling process.

Following the capture and control of the constituent parts we began to recombine these with the computer modelling environment to reproduce a form as close to the original sculpture as possible. In the physical process as each component was aggregated subtle adjustments in clay permitted continuity. In the computer modelling gradual refinement to the coarse mesh allowed the same. We 3d printed a decimated version of the original scan as a further physical reference to the actual ceramic form. Both physical versions of our target form were used extensively in this reconstruction process. The decimated original mesh was referenced into the model and SSM continued to facilitate this stage of the modeling by permitting the rapid evolution of a final form by iterating the following steps.

1. Artist identified which component part to add next and where
2. 3d modeller added this part to the coarse mesh
3. 3d modeller refined the mesh and compared the result to the original scanned, artist provided aesthetic analysis
4. Adjust other previously added components as necessary
5. Repeat steps 3 and 4 until satisfied
6. Return to step one until all components added

Once we had a close match to the original sculpture the team grew in order to examine the form in the context of the site. This phase involved artist, 3D modeller, and additional architects. Here we moved to a more complex phase - rationalisation and fitting of the architectural requirements to the sculptural form while still maintaining the original aesthetic qualities. We extended our previous mesh matching process to include the extraction to traditional scaled 2D drawings plans, sections and images. Using these,

the architectural team would sketch over the top (figures 13-15) to identify where the building functioned architecturally, and where we needed to make modifications. SSM made these modifications possible by providing global control of the position of the coarse mesh on site. By parametrizing the scaling and rotation of the mesh in all coordinate axes and we could make further local geometric adjustments and then refine the coarse mesh to check against the original form. One major adjustment that challenged the desire to maintain aesthetic qualities of the original was the proportions of the entire sculptural form. Originally it did not permit sufficient space for circulation and accommodation of the required program. The refined mesh had to be offset to accommodate the program.

In the ultimate phase of the process we continued to extract geometric data from the model and refined in detail specific spatial and constructive aspects of the proposal (figures 16 - 18). Different layers of the proposed construction were aligned with varying levels of mesh refinement in the SSM process. We could extract each of these domain specific levels by controlling the level of mesh refinement, mesh offsets. The correspondence between the geometry of resulting meshes allow very accurate coordination of systems and subsystems. While our drawings were ultimately for a competition the potential to use SSM to facilitate building systems coordination was very apparent.

IMPLICATIONS

Modelling method

In Architectural Geometry (Pottman et al 2007) a methodology of modelling with subdivision surfaces is described where the designer moves towards a specific goal in a linear way by subdividing and then manually refining the resulting mesh and repeating this subdivide-manual refine process until a satisfactory result is achieved. For us this resulted in unsatisfactory results with curvature discontinuities in the resulting surfaces. These kind of problems were unacceptable from both an aesthetic and construc-

tive perspective. In our approach we worked iteratively between the crude mesh and the refined mesh. Each time comparing the refined mesh to our original sculptural form and evaluated according to the original artistic aesthetics and the functional architectural requirements. When the results were unsatisfactory we adjusted the crude mesh and refined it again. We were therefore highly dependent on the results of subdivision algorithm and chose to use the Catmull-Clark method (ref). Several other subdivision algorithms exist and for future applications it would be essential to have a good understanding of the results in the different schemas.

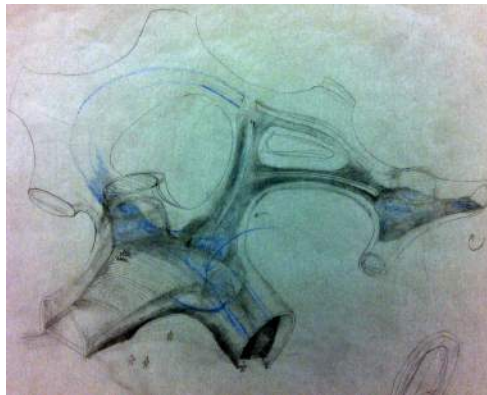


Figure 15
Architect's working sketch during form rationalisation

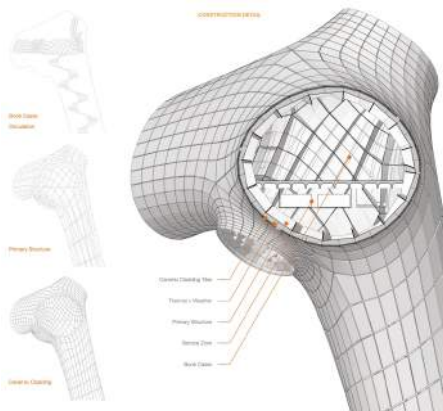


Figure 16
Construction detail of programmatic space inside subdivided form. Rapid iteration allowed for assessment of structural, service, and functional space and adjustment of offsets to suit

SSM and BIM

The use of a logically robust and parametrically controlled design process offers numerous advantages towards a BIM workflow that is amplified by the inclusion of the SSM process and the interdisciplinary benefits that come with it (figure 19).

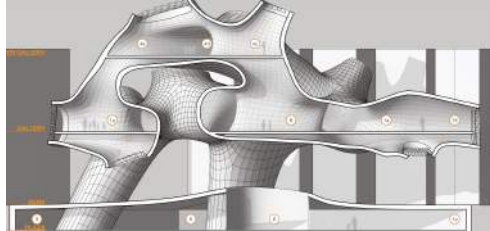


Figure 17
Using the tools built into the Rhinoceros software package, the team was able to quickly assess the results from form-finding against design criteria, such as relationships with surrounding urban fabric

The BIMForum Level of Development Specification [6] identifies that different elements of any given BIM model will progress to different stages of completion as the project progresses, akin to the analogy previously drawn between the process of subdivision and the progressive fine-tuning of architectural design processes as they proceed. Allowing for rapid iteration creates a thorough process for assessment of the implications of different proposed solutions within the context of the model. Combined with an automatic generation of construction documentation and potential partnerships with other consultants, contractors, and fabricators, the loop created is powerful in implementing designs that satisfy design criteria. The link between design and fabrication/construction is strengthened.



Figure 18
Renderings that establish a human scale can be extracted relatively quickly for multiple iterations of the project.

Performance analysis

The potential to undertake rapid analysis in practice as not implemented fully, and likely would proceed

with a project of this type if it were to receive further development past its current conceptual stages. The high surface area to enclosed volume indicates great potential for a skin that could capture solar energy, and optimization of panels could be rationalized using computational modeling. Other opportunities exist for extraction of design drawings, fabrication drawings, data sets for analysis, shadow casting, solar gain, physical model building, and many other benefits. The structural system was derived directly from the subdivision method, and likely would also undergo optimization in tandem with a larger consultant team as is common practice moving to another project stage.

Rapid Prototyping

Architecture is a unique discipline where due to time, financial, and other constraints the abstraction of space and form into a 2D drawing, physical model, or digital 3D model makes it necessary to understand the requirements of a design and convey the solution to stakeholders. Computational design is currently an integral part of many architecture projects. The team's unique workflow provided a relationship between the physical, tactile form, and the virtualized urban geometry of the city, extending the use of CAD technologies from a simple drafting tool to an instrument for interaction between members of a team. Team members could share their understanding of the particular issues as viewed through their own perspectives, and respond either digitally or physically in a joint learning process.

The use of 3D printing provides an intriguing avenue of further exploration, as it implies a workflow of creating a physical model, scanning, modification, and 3D printing to begin the process anew. By giving an abstract digital process tactile form, the outcome of the process would be considered from other perspectives than solely a digital one. In the documented process 3D printing was under utilised, the single 3D print of the original 3D scan of the sculpture and this proved valuable in the stage of matching our computation geometry to the physical.

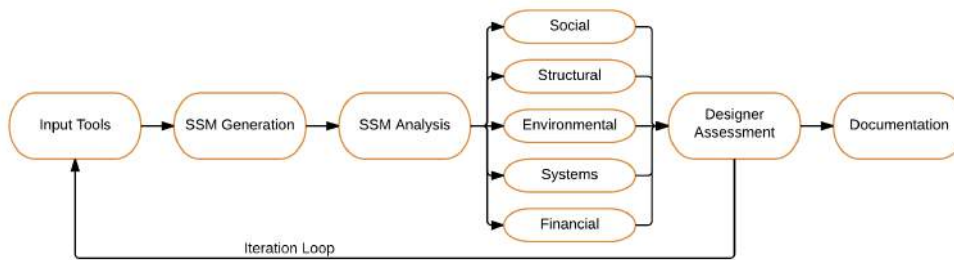


Figure 19
Iteration loop for
SSM process
demonstrating a
balance of
generation and
analysis. Not all
potential analytical
variables are
depicted.

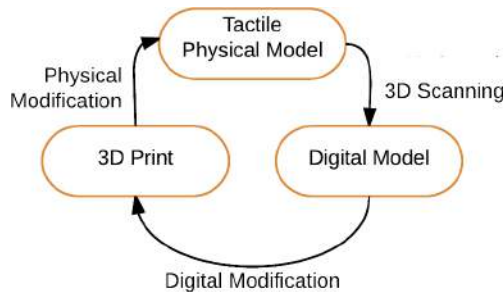


Figure 20
Proposed tactile
fabrication
workflow.

CONCLUSIONS

Our implementation demonstrates how it is possible to take advantage of SSM in architectural design, provided that the level of subdivision and required parameters for modification are carefully controlled. The dynamic nature of the SSM process facilitated an unusually direct connection between physical and computational domains as a result of its speed and responsivity. Working as a team, the process enabled the identification of issues and implementation of solutions in the urban context of the site in an unprecedented way. This was leveraged to foster communication within a design team formed of three generations of designers and artists, each with a very specific skill set and contributing a vital piece of the greater puzzle.

Through a process of analysis, decimation, and rationalisation we developed a language that described the topological features of the model parts. This directly informed the construction of coarse meshes which through SSM could be iteratively subdivided to produce surfaces close to the forms of original sculptural objects. By recombining the coarse meshes we were able to develop a model consisting of a control network for the entire building. After subdividing this network of coarse meshes the resulting polygon mesh could be quickly analysed and evaluated according to a series of architectural and environmental criteria. Manipulating the network of coarse meshes and evaluating the resulting polygo-

Interdisciplinary Collaboration

The Integrated Project Delivery process (IPD) which is emerging as the new norm of design practice due to technical and scheduling changes in the architectural industry requires a level of robust communication among disparate stakeholders in early design stages [7], and SSM has proven to be a viable avenue for rapid iteration and inclusivity. Our team was able to collaborate closely across disciplinary boundaries through the intuitive nature of the process in relationship to the physical and digital realms of design. The quick results as generated from the process allowed for rapid feedback that ensured all team members had a say in the design, without the emergence of "silos" of thinking due to poor lines of communication.

nal form enabled us to progressively converge on a final proposal. Further iterations of subdivision resulted in geometry describing the primary structure, secondary structure and discrete cladding panels

The ability to shift between coarse and refined mesh results by controlling the number of iterations permitted us to optimise the aesthetic and architectural goals using visual assessment by both the artist and the architect. This method offers great future potential in integrated practices for dynamic form-finding, and delivering projects that meet project goals

[6] <https://bimforum.org/lod/>

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