Design by Nature: Concrete Infiltrations

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The paper aims to address methods of realizing computationally generated self-organizing systems on a one-to-one scale with the employment of a singular material system. The case study described in this paper is the outcome of an investigation which has explored earth scaffolding, fabric form-work, and concrete materiality during an international three-week architecture workshop. Real-time generative form-finding methods based on branching and bundling systems in nature have been developed and simulated in an open-source programming environment. The outcome of the simulation stage has been analyzed structurally via Finite Element Analysis (FEA), results of which have served as inputs for the fine-tuning of the simulation. Final three-dimensional geometry has been fabricated by employing fabric, essentially forming the fabric form-work. Fabric form-work is then laid on top of the earth scaffolding, followed by the process of concrete casting. From a pedagogical point of view, the research focuses on the integration of digital design techniques between various design/architecture/analysis platforms combined with basic and advanced techniques of construction within a limited time frame.

Keywords: Simulation, Generative design, Nature, Earth scaffolding, Fabric formwork

INTRODUCTION  
Nature folds various functions into basic material systems through differentiation. The systematic diversity in the observed and microscopic world of nature occurs due to the ways in which basic materials, such as cellulose and chitin, re-order and self-organize themselves to form complex constructions of varying scales. Diversity in nature does not emerge from \textit{which} materials to use, but \textit{how} to use available materials (Hensel et al. 2010). In the recent decades, the complexity that is observed in natural systems has provided the inspiration for a new approach to design and construction, becoming an established part of the architectural discourse (Vincent et al. 2006). With the vast range of digital tools, the designer is now able to explore the correlation between the multiple subsidiary systems operating across a range of scales in all design related fields.  

Situating itself within the complexity paradigm and its design-oriented implications, the research investigates methods of realizing computationally generated self-organizing systems on a one-to-one scale with the employment of a singular material system. The case study described in this paper is
the outcome of an investigation which has explored earth scaffolding, fabric formwork, and concrete materiality during an international three-week architecture workshop. From a pedagogical point of view, the research focuses on the integration of digital design techniques between various design/architecture/analysis platforms combined with basic and advanced techniques of construction within a limited schedule. In this way, the complete process revolves around how students can understand the ways of transition from the digital paradigm towards physical fabrication and assembly processes with a fully hands-on experience.

The objectives of the research are two-fold. While real-world constraints through the implementation of advanced physics calculations in computational simulations are taken into account, attention is also given to how the digital paradigm and physical materiality can inform each other during design and fabrication processes. As such, it is argued that computational and physical attributes are two equally important aspects which have direct feedback on one another during the design and fabrication processes.

**METHODOLOGY**

A research methodology has been developed in order to test the research objectives. The design brief is to propose and construct a one-to-one scale pavilion made from concrete in a forest located in the south of United Kingdom within a limited time frame. Initially, real-time generative form-finding methods based on branching and bundling systems in nature have been developed and simulated in the open-source programming environment Processing. Key influences in working with branching systems have been their structural advantages coupled with the motivation to contextualize the design outcome in the natural environment of the forest.

Methods of transmitting forces over a given distance in the most effective way have been explored by Frei Otto and his team at the Institute for Lightweight Structures (Figure 1). The first method, minimal path system, links given points with detours to produce the least overall distance. In nature, the minimal path system can be observed in the self-formation of soap films. Structurally, this system is less effective for the transmission of forces as the outer support arms are loaded in bending. The second method, direct path system, connects every given point with a straight line to each other with no detours. Through this method, the forces are transmitted on the shortest possible path, but the overall path length increases drastically. This system becomes more effective if the points of force application are connected with beam ties so that the bars are compression loaded. The third method, namely the minimal detours system, can be viewed as a negotiation between the minimal path and the direct path systems. Synthetic analogy research about this method has been carried out by exploring the self-formation processes in moistened thread networks. In this setup, first of all the prearranged points are all connected with threads as in the case of direct path systems. The threads are then given a limited excess length, such as 8%, thereafter being dipped in water. The threads bundle with each other as a result of the surface tension of water. Even though the overall length of the threads is 8% longer than in the case of direct path system, the overall area to be covered decreases by 30-50%. Reviewing this method in a structural context yields the result that the forces to be transported are more optimized due to the concentration of paths, increasing the buckling resistance of structural members. Effectiveness of the system is increased more if the points of force application are connected with a beam tie. As a result, branched structures generated with minimal detours system use less material in a more effective manner than the ones generated with direct path system (Otto et al. 2006).

In nature, branched structures can be found in abundance throughout various plant systems. Materialized direct path systems can be observed in umbels, and materialized minimal detours systems can be viewed in bushes and shrubs. The difference between branched constructions in architec-
ture and nature lies in functionality. Whereas the branched structures built by humans are mainly designed to carry a structural function, the branched constructions of nature have the property of multifunctionality. In the case of plants, the branches need to transport water, minerals and products of photosynthesis for survival as well as maintain the necessary structural resistance against the various forces applied to the leaves (Otto et al. 2006).

In biological systems, self-organization refers to the process where pattern at the global level emerges from the interaction between lower-level components. The rules specifying the interactions between lower-level components rise from local information, without the interference of external directing instructions (Weinstock 2004). Swarm intelligence, a concept mainly used on research about Artificial Intelligence, is the behavior exerted by natural or artificial self-organized systems, being made up of boids/agents which interact locally with each other and their environment. These interactions lead to the emergence of complex systems demonstrating intelligent behavior on a global level (Reynolds 1987). The inspiration for generating swarm intelligence mainly come from biological systems, such as bird flocking, fish schooling, ant colonies, and bacterial growth. In the computational paradigm, agent-based models are used to create decentralized, self-organized behavior. These computational algorithms simulate the local interactions of agents in order to evaluate their complex behavioral patterns leading to swarm intelligence (Shiffman 2012).

In the context of this research, self-organization refers to form-finding methods directed at optimiz-
ing the load bearing capacity of structures through a process where the amount of material of the system is decreased as its strength is increased, while simultaneously having the ability to make local adjustments according to preferred architectonic qualities. As such, the digital simulations present a progression from the analogue-optimized path experiments of Frei Otto due to additional design constraints relating to gravitational forces, levels of adjusting bundling intensity on a local scale, and the ability to follow free form three-dimensional shapes. During the simulation processes, various iterations have been generated. The iterations vary according to the amount of paths, intensity of bundling force, the minimum and maximum distance ranges which bundling forces can influence, as well as the starting geometrical form. Initially, a starting geometrical form is created in a three-dimensional modelling software, McNeel Rhinoceros, and its iso-curves in the U and V directions are extracted. These curves are then divided into a specific number of points. The point coordinate data is then exported from Rhinoceros as a text file and imported into Processing. In Processing, these points are defined as nodes which are connected to each other via particle-spring systems; therefore, it is now possible to create real-time dynamic interaction between them. At this instant, the mathematical description of minimal detours system as a function of proximity is applied to the nodes. If the nodes are within a maximum neighbouring distance to each other, then a force which bundles them together is created. The force is described mathematically as the average vector from each of the nodes towards the neighboring nodes; therefore, the nodes within the neighboring range begin to move towards each other. This force is applied until the distance between the nodes reaches a minimum amount specified as a parameter. The maximum amount of magnitude for the bundling force is determined as a parameter in order to limit the strength of bundling. This magnitude grows by an increment of 0.00005 as the z-coordinate of the nodes increases, in order to provide for more openings in the higher ranges of the form. The calculation of the bundling force is repeated for every frame of the simulation, whereby the particle-spring system reaches its resting position after all the nodes are bundled together.

Figure 2 demonstrates instances of the Processing simulation during its course, starting with the paths in their initial position and finally concluding when all the paths reach their resting position as a result of the applied forces. It must be noted that a shell form has been opted for after initial tests with free-form surfaces, as concrete’s strong compressive capacity makes it suitable for shell structures, a system containing mainly compression forces. After the generation of various iterations, a design option is selected according to criteria including the desired number of openings and anticipated structural stability.

The outcome of this stage, visualized as curved geometrical elements, is exported from Processing as a text file comprising the coordinates of points which form every curve element. This data is then imported to McNeel Rhinoceros and given structural thickness. The radius of each branch in the model is 15 cm. The model is evaluated via FEA analyses in Rhinoceros’ plug-in Scan&Solve. The structural analysis is carried out as a solid volume analysis, the selected material properties belong to high strength concrete (Table 1), and the model is analysed under its own self-weight. The total displacement values gained from initial FEA analyses serve as inputs for re-adjusting the parameters of the Processing algorithm through various iterations. It is observed that nodes where several branches come together perform inadequately due to buckling. Therefore, in the final iteration the maximum neighbouring distance has been decreased to generate 2 branches per node in order to decrease buckling. The final parameters related to bundling can be viewed in Table 2. Figure 3 illustrates the resulting configuration of optimized path members generating the pavilion and the corresponding total displacement values, which range between 0.000149382 meters and 1.08157e-12 meters.
Figure 2
Instances of Processing simulation demonstrating the applied forces on the initial path network.

Table 1
Material properties for high strength concrete.

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus</td>
<td>3,000 kN/cm²</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>2,100 kN/cm²</td>
</tr>
<tr>
<td>Specific Weight</td>
<td>23.3 kN/m³</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>NA</td>
</tr>
</tbody>
</table>

Table 2
Parameters of branching / bundling operation in Processing.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of divisions</td>
<td>20</td>
</tr>
<tr>
<td>bundlingDistanceMax</td>
<td>0.6 m</td>
</tr>
<tr>
<td>bundlingDistanceMin</td>
<td>0.1 m</td>
</tr>
<tr>
<td>bundlingForce</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

The objective of the next stage is to transform the three-dimensional geometry into a two-dimensional layout which can then be cut from fabric. For this purpose, the final geometry has first been sliced radially into 12 pieces. Each piece is flattened via the Rhinoceros Squish command, which is developed to flatten non-developable surfaces. The parameters of the command are adjusted to match those of an elastic material in order to control the compression and stretch amounts realistically. Figure 4 shows one of the slices of the final output, both as a three-dimensional geometry and two-dimensional pattern with the corresponding compression and stretch amounts, which have minor numerical values. The resulting two-dimensional outputs of this stage are then marked on fabric via CNC router and stitched together, thereby creating the fabric form-work for concrete casting.
In the concluding stages of the process, the scaffolding for the pavilion is assembled from earth in the forest (Figure 5), forming a second point of integration with the environment of the context. The overall form in the digital simulations is adhered to by the inclusion of timber ribs serving as guidelines during the earth scaffolding construction process. The fabric formwork is then laid on top of the earth scaffolding, followed by the process of concrete casting (Figure 6). The structure is made of a special concrete mix with fiberglass additives which has enabled it to be cast, dried and held strongly in place in a period of several hours without being limited by the constraints of applying conventional reinforcing systems such as re-bar. Finally, the earth scaffolding is removed and reunited with the surroundings (Figure 7). Being 2.1 meters tall and 4.4 meters wide, the fabrication and assembly of the pavilion has been realized within a period of one week (Figure 8).

RESULTS
The design and fabrication processes have demonstrated the strong independence between the digital and physical paradigms in design. While the computational simulations have taken real-world constraints into account with the implementation of physics behaviour, the material properties of concrete and the correlations between earth and concrete have been some of the critical aspects which could not have been predicted via the simulations. Due to the humid conditions in the forest environment, the earth scaffolding became condensed which in turn restricted the settling of the fabric and concrete while concrete was being poured. Therefore, future work needs to incorporate CFD (Computational Fluid Dynamics) simulation of concrete in the digital environment in order to allow for more precise control of the final physical output. It has also been witnessed that the density of the fabric formwork is crucial in manipulating the behaviour of concrete. An ideal formwork setup would comprise fabric with less density, in other words more openings, in the lower parts of the scaffolding in order to accelerate the cur-
ing speed of concrete.

Data exchange between Processing and McNeel Rhinoceros has been smooth due to the utilization of the import and export functions in Processing as a text function. As such, the output model has the advantage of high portability - it is essentially a geometrically precise 3-dimensional spatial model of nodes and lines connecting them with data attached.

Further observations have been made regarding the structural thickness of the final output. In terms of structural performance, if the diameter of the branching elements is decreased towards the higher parts of the pavilion, total displacement values will also decrease accordingly. Future work on the research area will incorporate this principle during the computational phase of explorations.

The analysis process which is characterized by the initial creation of an output model in Processing and the application of FEA tools in the second step proves to be of a linear nature whereby design and analysis procedures cannot create feedback for each other. It is necessary that this process is altered to move away from a linear setup towards a generative one by employing real-time FEA analysis concurrently with the Processing simulation. This procedure can allow for a feedback loop between Processing and the FEA platform such that the nodes in Processing can regulate their position and concentration according to the progressive results obtained from FEA.
DISCUSSION
Throughout the design, fabrication, and assembly processes, the progressive inter-relationship between different simulation software has been a key driver in recognizing the ways of integrating architectural criteria with the structural performance of the pavilion. Furthermore, the comparison between the digital simulation of the architectural output and the final output, the pavilion itself, provides useful information to be considered and embedded in the future digital simulations. Overall, the research aims to illustrate the architectural possibilities of using concrete in a non-conventional way, directly connecting computational design methodologies with digital fabrication processes.

The pedagogical approach engaged in this workshop aim to establish ways of integrating the conceptual and practical aspects of innovative design methodologies. The major intention is to enable the students to grasp the theoretical, computational, and physical advantages and constraints of the described methodologies. It is believed that active engagement with the procedural levels of creation from the early stages of architectural education has a significant contribution to the student’s understanding and development in the design context. As such, it has been observed that a pedagogical setting incorporating an intensive learning process with a limited amount of time has rendered students to be more absorbed and involved in all stages of design and making.

REFERENCES