THE RISE – MATERIAL BEHAVIOUR IN GENERATIVE DESIGN

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1 The Rise – installed in the atrium space of the Fondation EDF Espace in Paris 2013

ABSTRACT

The research-based installation, The Rise, is led by the concept of a growing architecture able to sense and dynamically adapt to its environment as it grows into form while continuously reacting to its own material performance and behavioural constraints. This process is enabled through the careful integration of digital simulation techniques with multi-hierarchical generative design approaches. Aggregations of variably sized bundles of rattan core multiply, bend, branch and recombine into a distributed assembly that manifests an alternative to traditional structural systems. The hybrid approach links a material system with simulation and the iterative generation of geometry through a process of calibration at different stages of design. The project leverages emerging computational strategies for growth in a model for an architectural practice that engages the complexity and interdependencies that characterise a contemporary design practice.

INTRODUCTION

The role of representation and prototyping is challenged by recent developments wherein material performance operates as a key driver of architectural design. Traditionally, the design process focuses on dead geometry, as (Evans) stated, and any investigation of the interrelations and behaviour of environment, energy and material—which may be considered through intuition during the initial design process—are generally relegated to a secondary post-generative analysis. In this process, a parameter space is developed into which a generative model is located in pursuit of an appropriate design solution expressed in a geometrical form. The performance and behaviour of this model is then tested in a physical manifestation or a digital simulation. Repeatedly cycling through this process of parameterization, generation, simulation and analysis enables the designer to optimize for selected effects and characteristics of the model (Kolarevic). Often in fact, the designer will deploy evolutionary algorithms to systematically interrogate this parameter space with the goal of optimizing one or more variables toward a pre-determined value. A potential shortcoming in this approach lies within the length of the feedback loop created. Parametric design tools are practical but they effectively rely on the definition of specific base infrastructures that are resistant to change during the design process and over the lifetime of a model (Scheurer). In order to establish a stable base for the needed feedback loops it is essential to have models with fixed topologies or rigid initial parameter states. Hence, attempts to model for the changing state of both model and environment and finding appropriate design solutions face the fundamental limits of the computational models that underlie contemporary practice. How can the rigidity and overly deterministic behaviour of our models be overcome, and how can a more direct feedback mechanism become an integral part of them?

Natural plant growth presents one diagrammatic framework for developing a modelling approach that is able to adapt to internal and external changes. Plant formation is accretive, and successive growth iterations depend on the physical properties of previously accumulated matter in relation to both itself and its environment. The mechanisms that describe the motivators and geometric principles of plant morphogenesis are known as tropisms, which is derived from the Greek "Tropos", meaning a "turning". It was first proposed in 1927 in the Cholodny–Went model, and is today widely used to describe the continuous change and transformation expressed during growth. As described by Esmon et al (2005), "plant tropisms are operationally defined as differential growth responses that reorient plant organs in response to direction of physical stimuli." Examples of tropisms include those reacting to light inputs (Figure 2), gravity, electrical, chemical or hydrological environments or touch. In plants, the biological mechanism for differentiation during formation is understood to be in

2 Phototropism in a plant

most instances auxin, a hormone that directs new cellular growth and coordinates the emergence of the plant's geometry. Within the plant's metabolism, the presence or absence of auxin triggers the distribution of those available resources required for growth. The Rise investigates how this diagram of growth exhibited by living vegetative systems can inform computational models in the creation of a self-propagating structure. We ask whether strategies for growth can operate as drivers of a generative system that is aware of both its environment as a driver of algorithmic form generation, and itself as a driver of material constraint and behavioural characteristics. The installation is commissioned by the Fondation EDF and is especially fabricated for the exhibition "Alive – Designing with Living Systems" that takes place from April–September 2013 in Paris. The installation operates on an architectural scale and is site specific to the gallery atrium at the Fondation EDF's "Espace", reaching from the ground to the ceiling.

The primary conceptual driver for the project is the idea of a growing architecture: similar to a plant, the installation model possesses a series of internally coded algorithmic responses that guide branching and growth through material accumulation, orientation and distribution.

As a designed system The Rise can combine behaviours of different vegetative systems, one of these is self-grafting. Although this behaviour is often associated with human intervention (Figure 3a), it also occurs naturally in some plants, such as certain species of ficus and fig (Figure 3b). In such instances, branches can meet and grow together in new circular relationships that enable structural performance. In this way, the installation is activated as a diagram of natural growth processes and mimics nature's manner of creating structural performance through strategies of redundancy and material distribution, reinforcing these traits with the more unusual hybrid growth methodology of self-grafting (Figure 4).

3a Self-grafting through human intervention

3b Natural self-grafting plant formations

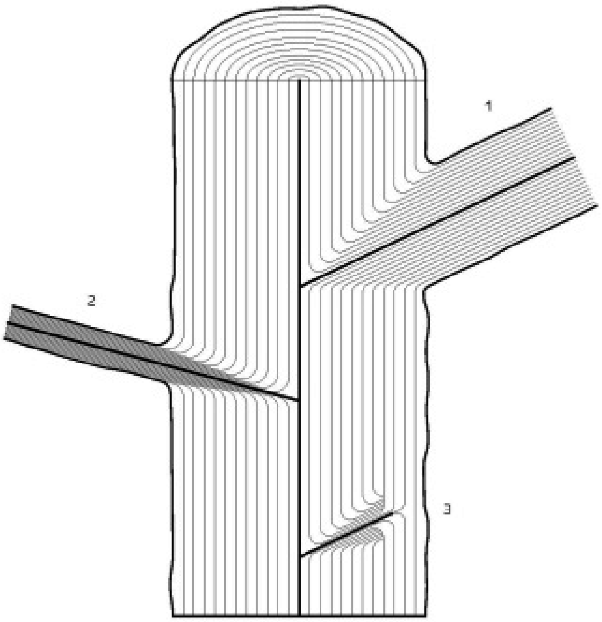
3c Natural self-grafting plant formations

The installation model and assembly logics also emulate the fibrous material lamination mechanisms exhibited in tree growth. In trees, growth occurs through the layering of multiple types of long and fibrous cells on the perimeter of the trunk, which are arrayed to achieve an integrated structural and nutrient distribution network. During normal growth along the trunks and branches, these long cells are generally arrayed parallel to growth direction with some variation in favour of helical growth occurring in certain species at both early and late-age growth. At branching moments, however, these fibres are cross-laminated to provide multi-directional resistance in the formation of a natural moment joint (Figure 5).

Rattan core is the primary material utilized in The Rise, as construction material and as well as inspiration for the programming of the behaviour of the artificial system. Rattan Core wood is a vine-like palm that grows up host trees in constant search for light in the dense jungles of Southeast Asia. The material used for the installation is sustainably harvested in Malaysia, where the wood is knife-extruded into round sections (the installation relies on thicknesses of 5 mm, 10 mm and 19 mm). The woody material is soft and is comprised almost entirely of a collection of continuous and tightly packed hollow fibres. These can be differentiated from other long woody plants like bamboo, which instead are regularly broken into linear segments by a series of bracing nodes that enable self-support. This organization strategy is tied to a rattan's reliance on other plants for structure, and it allows the rattan to more efficiently transport water and nutrients from the ground along winding branches for rapid growth and its ability to bend in extreme angles towards the sun. This flexibility also affords the material improved resistance to breaking, and its long fibres endow it with high tensile performance. These characteristics—resilience to breaking, ease in bending, and tensile strength—are all maintained post-harvest and make rattan a preferred material for furniture and basket making in South Asia and popular throughout the world. In its natural habitat rattan is structurally dependent on the structures of other trees, and it grows through a process of closely hugging its hosts.

Through a process of tight bundling along a normal trunk and branch growth, and multi-directional active bending collections at each branching moment, the rattan core is used in The Rise in such a way as to mimic the behaviours of cellular vegetative growth. Crucially, the highly flexible nature of rattan exhibits bending behaviours that facilitate both fabrication as well as the calibration of the digital design system in its continuous simulation of material characteristics during morphogenesis. The model's dynamic topology is then directed to branch and multiply according to its internally encoded logics as a response both to its environment, but furthermore in direct response to its own behaviours in light of continuous accretion and simulated material behaviour. Through these logics the installation explores the use

4 Scaled model from the design process speculating algorithmic growth and networked behaviour through branching and self-connection



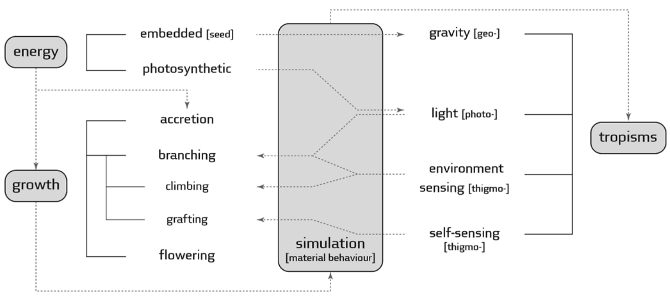
5 A simplified section of a branch reveals its complex fibrous setup, which works in compression as well as in tension

of highly redundant and distributed systems as an alternative to traditional structural systems. Instead of leveraging the post-formation optimization of certain elements, we grow a multitude of intersecting members that combine to form an integrated structural network. In this vision architecture is not a static formalist proposition, but is instead continuously adapting to the dynamics of its surroundings and its own material constraint while it grows into form.

SYNTHESIS OF ALGORITHM AND SIMULATION

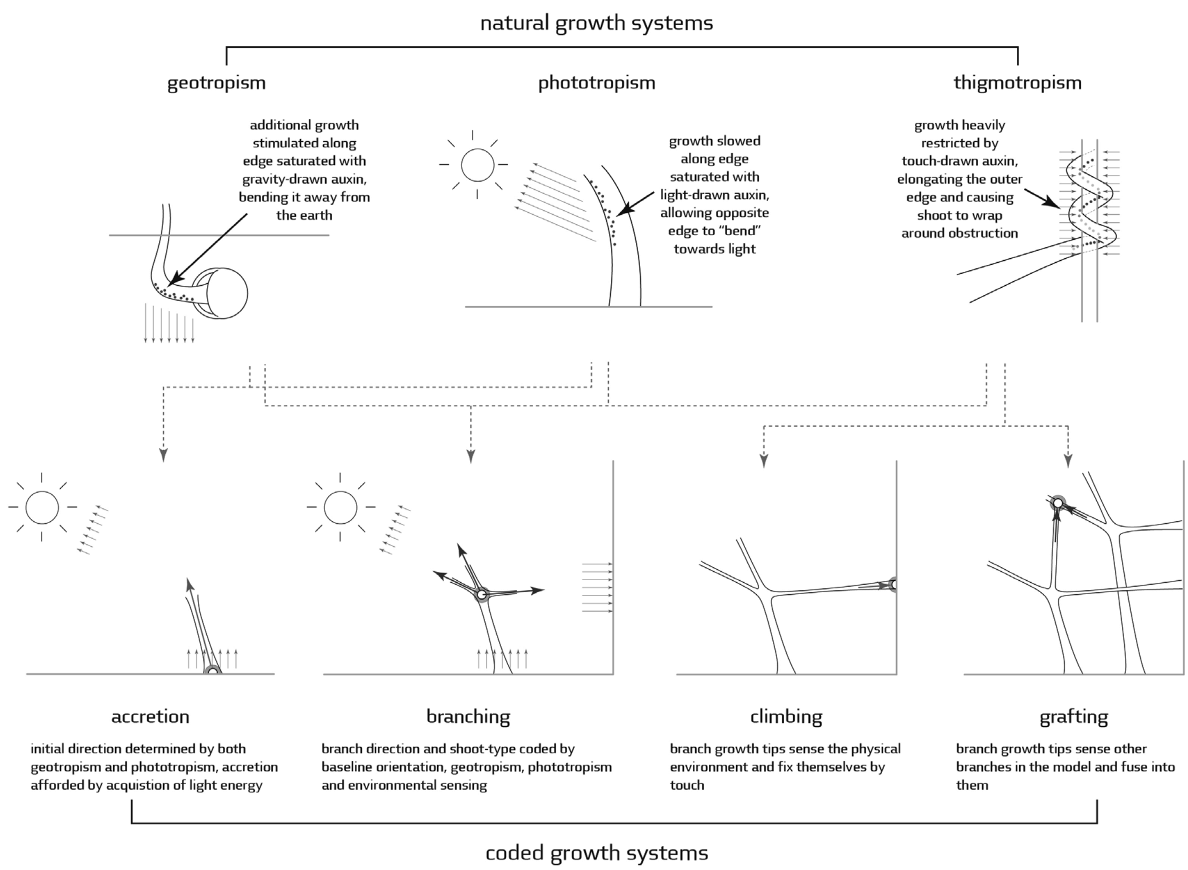
The installation's model emerges from an adaptive growth algorithm that combines the simulation of plant growth logics with an active and continuously running particle-based physics simulation system. These elements work in concert to activate the characteristics of the rattan core as primary contributors to form generation, and to enable an algorithmic procedure that is informed by both self and environmental awareness. The Rise has been developed to operate as a climbing growth organism. It utilizes structural "shoots" and gripping feet that identify and cling to their physical surroundings as vine-like plants do and achieves structural triangulation through a process of self-grafting.

The Rise relies heavily on emulating a system of plant-like tropisms as a series of diagrammatic drivers in form generation and performance. For our modelling process, we focused on only three types of tropisms: phototropism (light-driven response), geotropism (gravity-driven response) and thigmotropism (touch-driven response). In plant formation, these responses are registered through the triggering of a hormone such as auxin. These hormones will often suppress (or activate) growth in certain cells or locations by restricting (or promoting) energy-based resources in order to allow for an uneven and ultimately directed cellular growth. Again via Esmon (2005): "Each tropic response has its own special suite of molecules that are necessary for proper signal perception, signal amplification and attenuation and elaboration of the growth response. While the establishment of hormone gradients is a required step in each response, it's not the hormone that does the dirty work. Auxin, for example, acts indirectly through many different proteins to induce a growth response." This localized cellular variation serves to orient the plant according to an internalized rule system that ultimately produces goal-oriented growth and organizational emergence. In our model we interpret tropisms through the algorithmic deployment of directional orientation and task assignment during branching and those further topological transformations introduced in the form of the self-grafting and climbing behaviours described above.

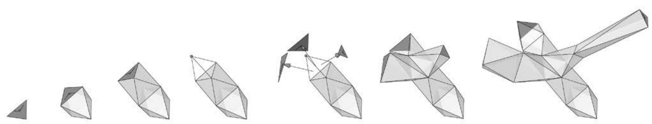


7 System for continuous growth filtered through the results of an on going simulation of physical properties during morphogenesis

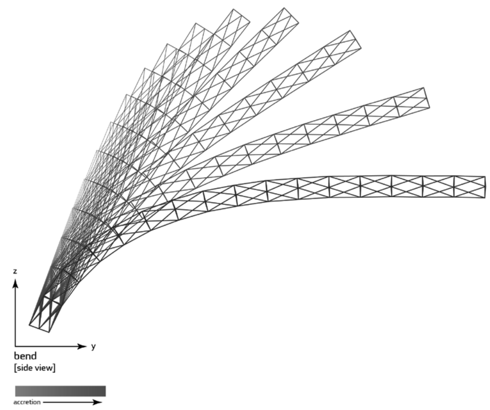
In addition to this application of tropism-like characteristics, our model also relies heavily on the diagrammatic simulation of light providing energy for growth activation, both in terms of orientation (phototropism) and substance (material accretion). To achieve this, our model then uses a series of energy variables that are distributed according to a local branch's proximity to a light source: the closer the growth tip of a branch is to the light, the more energy it is given for the three distinct growth processes of lengthening, further branching and flowering. Energy is portioned out and incrementally accumulated for each of these actions by growth tip according to parameter settings assigned by the designer, and at each growth phase each tip tests the stores of energy is has available to execute any individual action. The threshold for accretion, for example, is set lower than that for branching which in turn



6 Diagrammatic foundation of plant tropisms for algorithmic goal-oriented model coding



8 Minimally triangulated modular accretion and branching logics for management of spring-based system and growth/ branching topologies

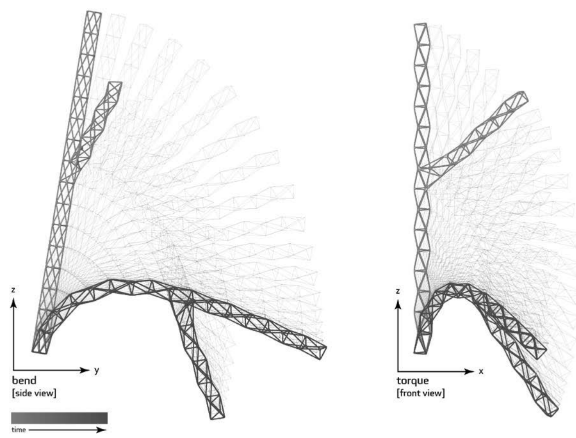


9a Bending under self-weight as a function of growth over time captured

is set lower than that for flowering. If a growth tip achieves the energy required for branching, it passes any other accumulated energy on to its child growth tips. Most crucially, the modelling of tropisms and simulation of energy is tightly coupled with an ongoing physics-based simulation of geometric bending and twisting under self-weight. This endows the growth model with the highly pliable rattan material characteristics during its formation.

Since the model is allowed to embody the characteristics of an active-bending structural system during its compilation, it emerges as much as a non-deterministic material response to its own geometry as it does to the integral formational algorithms that comprise the rules for its modular accretion. Each successive phase of growth is then actuated through the accumulation of new energy and the model's reading of both environment and its continuously moving place in it, due to both material aggregation and dynamic bending behaviour.

Careful management of model topology is instrumental for all aspects of the recursive growth algorithm as well as for later use in the production of detailing and fabrication systems, it is also essential to the embedded continuous physical simulation. The model exhibits its growth through the accretion of minimally triangulated modules, which are managed in a mesh (Figure 8) and that make up the core of the computational mechanism. Each open face of the mesh is identified as a growth tip that has the capacity to be activated by multiple drivers. The three points along each tip define a local coordinate space that serves as the nexus for several operations. Included among others are proximity testing mechanisms for the simulation of energy acquisition and for the interpretation of thigmotropism through grafting and climbing. The growth tip coordinate systems also provide the directional sensing necessary for multiple operations. New branches are assigned roles as either light-seeking elements or structure seeking elements based



9b Hierarchical assembly - standard units that combine to produce irregular structures based on hierarchical assembly

on their orientation in their environment. As a growth tip branches it forms a tetrahedron, the new open faces of which provide the base point for each new branch and its local coordinate system used for the orientation testing in this role assignment.

The mesh is managed such that its point, edge and face topology is registered and deployed in a custom-written particle-based spring and gravity simulation system. Early iterations of the model sought to embed distinct bending and spring forces in this system, but the constraints of this approach were revealed in its failure to realistically account for torsion and orientation during branching. The triangulated system developed in response to this accommodates not only the orientation and modular accretion tactics used for growth and tropism interpretation, but its truss-like organization also results in a configuration that allows for a wholly spring-based approach that simulates active bending, the retention of orientation during branching and torsional behaviours.

10 Overall generation with registration of absolute stresses derived during formation in the spring-based simulation engine, and local assignment of total material thicknesses according to this registration

Therefore, this mesh becomes a means for full model integration: it combines the simulated physical performances with multiple custom classes used for capturing vital information about the model's growing, branching, grafting and flowering events. The spring-based system also endows the model geometry with direct indicators of material performance. For this installation, measurement of spring lengths versus their baseline as they react to new algorithmic growth module accretion generates the data regarding deformation in both tension and compression which is crucial to the sizing and distribution of rattan members during detailing and fabrication (Figure 10).

Each growth iteration can then be identified by a three-fold cycle that includes: (a) environmental sensing in the form of orientation according light-source location and gravity, as well as proximity feeling for both itself and its physical surroundings, (b) local measurement and distribution of accumulated light energy for direct growth, branching and flowering, and (c) the simulation of physical form and material performance as a result of accretion. So rather than sequencing parameterization, generation, simulation and analysis into a series of discrete events, The Rise seeks to collapse this process into a tightly integrated synthetic whole.

DEVELOPMENT OF A BESPOKE FIBROUS MATERIAL SYSTEM

In an analogue to the tree climbing rattan, The Rise utilizes its environment for structural support. In difference to rattan The Rise can graft to itself. This creates redundant triangulation which enables it to manifest a more dynamic geometry as it increases overall structural strength. In its built instantiation, The Rise grows from two seed points at the columns of the gallery and bends under its own weight.

The assembly logic is expressed as a series of struts and connection nodes. Each strut is comprised of a tightly packed bundle of variably-sized rattan elements that behave as primary structural members and tie related connection nodes together. Each connection node is formed using the active bending properties of its composite rattan members in opposition to one another. Variable sizing in each member, according to their topological arrangement, is a registration of the orientation derived from the digital growth and simulation model (Figure 11).

As such the material's systematized elastic deformation (active bending) is an integral part of the system's architecture (Lienhard, 2012), and is used actively both in the creation of branching points and as a calculated part of the member sizing and distribution. Embedded information about the material's minimum allowable radius and bending behaviours couples with orientation and deformation information provided by the simulation to dynamically size members at each node and along each strut.

Along the struts, the efficiency of the bundling behaves like a textile in that it relies on friction between fibres. In The Rise, the necessary cohesion between fibres is created both through a strategy for maximizing the continuity of individual rattan members (Figure 12) through multiple connection nodes and through a series of locally customized compression rings—or "packing nodes"—made from CNC milled HDPE. Although a matrix material such as in wood or composite fibre products (Nicholas 2012) would afford a higher degree of structural efficiency, the taken approach considers the constraints of on-site installation and the engagement of the fibres with the connection nodes.

Branching is used in vegetative systems to maximize coverage for solar gain. For this biomimetic installation, it is then essential that The Rise to grow towards the sun. Branching moments also define weak points within the structure of a vegetative system. To combat this, plants develop highly tensile and elastic joints between the branch and the trunk. Where a crotch might seem to be a simple split, woody plant growth patterns create interwoven fibres that provide stiffness and elasticity in multiple directions. This cross weaving inspired the nodes of The Rise, where fibres are interwoven through the distinct connections between each member incoming to each branch node. Here variably sized and accumulated opposing rattan members in each node define the resulting orientation of each outgoing strut. These opposing rattan members in each connection node are organized again by a series of locally customized CNC milled HDPE elements—called stars—except that these work not as compression rings but rather as organizing and guiding systems for reorienting and managing the complex rattan member topologies that emerge from the meeting of multiple struts.

These stars are designed along with the packing nodes as an integrated system (Figure 13), where complex topological relationships are registered and managed both within each connection node's set of stars and between each connection node through each strut's packing node system. Through these systems, information derived from the growth/simulation system regarding geometry and material thicknesses is registered through the installation's fabrication logic. Individual rattan members are allowed to bundle and laminate in diagrammatic emulation of the same bundling and lamination that occurs in woody plant fibres that grow in response to their environment.

SYSTEM CALIBRATION

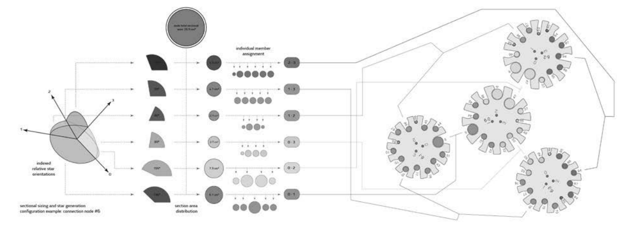
The development of the material system and its generative modelling process ran in parallel. A series of material tests used to engage in physical generative modelling techniques and to measure the rattan's bending capacities, and prototypes operated as investigations into the nature of the rattan's behaviour. These tests yield crucial data related to a number of parameters that informed the model's growth algorithms, physical simulations and final detailing processes. Included here are the measurements of bending load capacities, the composition of different sized members into the tightly-bent formations that define the model's branching node geometries, as well as analysis of the dynamic and time-dependent features related to the minimal bending radii allowed in variable material thicknesses.

In the case of the modelling process for The Rise, calibration of both the simulation in terms of bending performance as well as the fabrication system, member number and thickness is informed by the anticipated load but as well by the desired angles within this truly three-dimensional node. Observation of actual material configurations directly informed the system developed for calculating the material composition of each opposing connection strand in any given element. For example, for any four-point node topology, there are a total of six topological connections (from points 0 to 1, 0 to 2, 0 to 3, 1 to 2, 1 to 3, and 2 to 3). Within each node, those two elements that have been grown with the least bending are afforded the highest contribution of available material, such that their bending strength is greater than their neighbours (Figure 11 and Figure 14).

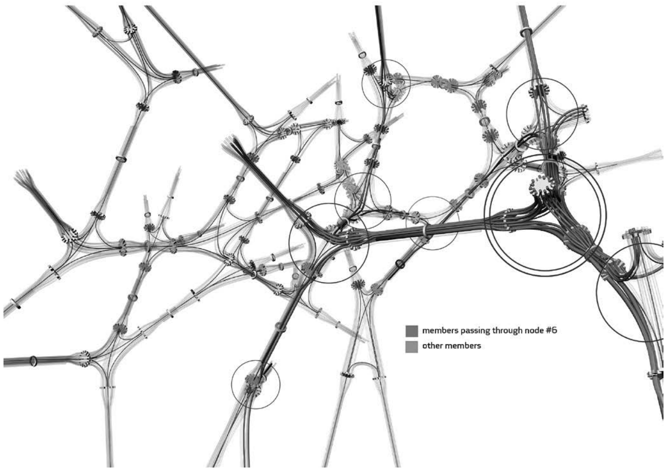
In conjunction with this, the total material in each node is dictated by the amount of deformation any node is required to resist, as anticipated through the simulation-based modelling process. Therefore, the total amount of material designated for any given node is distributed across each topological connection possibility according to both the total amount of resistance required of a node and the local geometric demands of each topological connection's angle. All of these tactics were fully informed by the empirical observations of the rattan in the various material tests executed.

DISCUSSION AND CONCLUSION

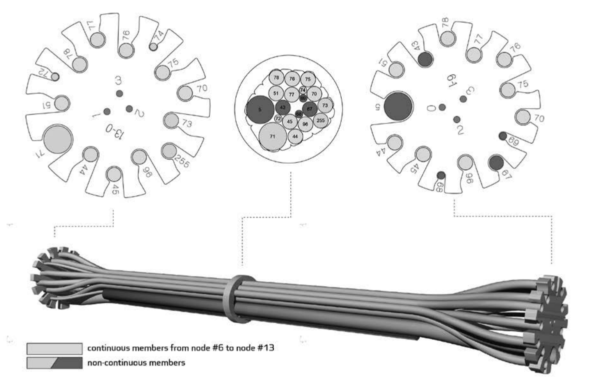
The Rise successfully creates an integral and tightly looped relationship between simulation and generation in architectural design. The collapse of the space between generation, analysis



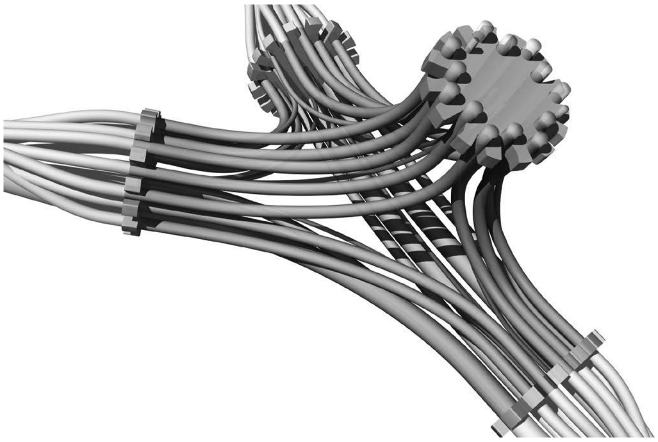
11 Synthesis of local active bending deformation with connection node branch orientations into member sizing and orientation for fabrication



12 Generated detailed model demonstrating dynamic continuity of fibres



13 Topologies between separate star elements through a packing node (star|packing node|star) topology, with member continuities



14 Render highlight of variably-sized oppositional bending elements defining the geometry of a connection node

15 Detail of assembled structure with dark guideposts instrumental for the assembly of the structure

and feedback distinction reduces the distinction between each to a brief moment of internalized computation. With such a tight feedback loop in place, a system awareness emerges that is able to directly couple generative strategies with material behaviour and consequence such that subsequent accretion and organization directly relies on accumulated geometry and performance characteristics. The use of this relatively simple spring-based approach for the generation of the geometry of an installation is sufficient for a proof-of-concept, but there is undoubtedly a great deal of further research that can be pursued to locate a broader base of simulation system inputs within iterative growth cycle and continuous remapping of the parameter space. Although the approach taken in the programming of the system shows a great amount of resilience towards changes in the environment as to the underlying assumptions and constructions on the material level, further opportunities exist to more directly couple fabrication logics into the generative design process itself. It may be possible that further considered use of the material, geometric and organizational properties in such a hybrid system could operate as further direct inputs in the refinement of the generative modelling space.

The Rise (Figure 15) demonstrates as well that the integration of feedback needs to take place on several levels and at different time steps during design development. While the integration of the described calibrated simulation of general bending behaviour is effective in this design generation process, further integration steps and research development will be necessary to determine the viability of such an approach on a detailed design level.

Opportunity for further integration lies in a better translation between material testing and the calibration of the simulation system. System-wide bending behaviours and those related to oppositional geometries along each connection are extracted from these parallel physical modelling processes. Meanwhile, these are wholly empirical in the sense that observation is translated into both simulation model and final fabrication configuration based on a series of localised tests. There is significant space to better code local physical characteristics into the simulation system as a means to further refine the relationship between digital feedback and anticipated physical performance. In its current state, The Rise relies heavily upon approximation and global behaviour parameterization. Therefore, while the local properties are determined according to their differentiated responses and deformations within this global setup, it should be possible to refine the model such that these properties themselves are set during simulation according to a more localized feedback system. It is only through continued iterations in the development of such an integrated simulation systems that an adequate level of precision for design on an architectural scale can be established. This step currently exceeds the capacity of the physics-based system as currently configured and utilised.

Where the design with generative systems can only take place through the configuration of the framing conditions and assumptions for the internal rule set (Tamke 2010), the use of simulation in a design integration requires the use of adequate system calibration. This system calibration was characterised in the case of The Rise through a series of feedback loops between assumption and experiment, with each new insight leading to new questions and refined assumptions. Where the process of the calibration of simulation is well understood, standard and absolutely necessary in other disciplines (Winsberg 2010) it challenges the architectural profession and the scale of its engagement. The Rise shows here how the integration of the development of the digital model and the physical systems allow for the cross seeding of information and the mutual increase of knowledge.

This knowledge might give the system more abilities or determine its behaviour in a better way. The integration of strategies of growth mean on the other side that the system cannot be informed about an optimal state it uses moreover its resilience to adapt its growth to a changing environment which includes the system itself. This cannot be understood as a neutral entity in an environment. In contrary it is active and is as much influenced by an examination of its own state as by changes of the environment, hence a preconceived optimization goal is not permitted. The Rise can therefore only be understood as a speculation of a more integrated future for design.

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