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Paper: Adaptive Structure: A Modular System for Generative Architecture

Topic: Architecture

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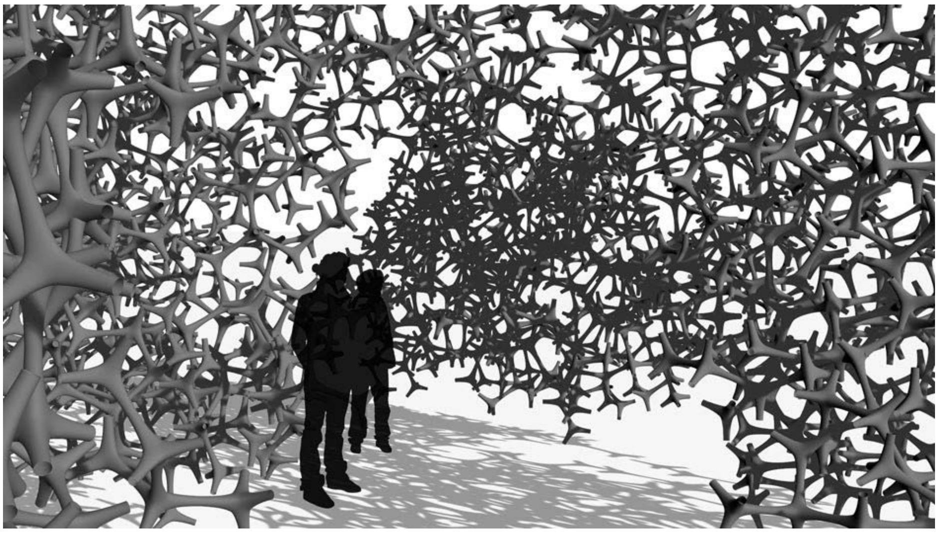
Abstract:
Complex spatial phenomena necessitate adaptive architectural design solutions. Consequently, physical space should evolve in response to shifting programmatic requirements and environmental stimuli through a process of structural adaptation, rather than being an immutable permanent entity. The aim of the research presented is to utilise an algorithmic, self-organising system in order to generate emergent, adaptive structures composed of mass-producible modular building components.

Diffusion-limited Aggregation (DLA) is a model for natural morphogenesis which is capable of generating biomorphic aggregate structures. It is an emergent, self-organising process in which randomly moving particles attach to a continuously growing cluster of aggregates. Because the cluster has potential for infinite growth, its process can be started and stopped. Additionally, the cluster can be made subject to environmental complexity through manipulation of aggregation probability. The model of DLA thus presents one possible mode of thinking and production for an adaptive structural system.

This paper introduces a case study in which a modular material system was developed based on the morphogenetic principles of DLA. Initially, the terms self-organisation and emergence will be introduced as an overarching research paradigm, thereafter DLA is explained in detail. The case study shows possible architectural implications as well as the technical detailing of the aggregate parts. The results of the case study will be discussed and further developments outlined.



Interior perspective exhibiting structural adaptation and spatial nuance

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Keywords:
Diffusion-limited Aggregation, DLA, emergence, self-organisation

Adaptive Structure:
A Modular System for Generative Architecture

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1. Introduction

Complexity theory provides a mathematical understanding of the systematic process from which complexity emerges. As opposed to reductionism (i.e. closed systems and linear relationships), complexity theory focuses on the collective behaviour that emerges from the milieu of interactions within a multitude of singular components. These interactions take place at all imaginable scales, from molecules and cells to ecosystems and climates. The complex is heterogeneous, composed of many varied and interdependent parts, which all behave uniquely based on encoded processes and specific environmental conditions [1]. Consideration for the natural complexity of ecological systems begins to provide a comprehensive understanding of the natural environment and its inherent intelligence.

Emergence and self-organisation, two generative processes found in nature, often occur in complex systems, usually in combination. De Wolf and Holvoet propose a working definition for emergence: “A system exhibits emergence when there are coherent elements at the macro-level that dynamically arise from the interactions between the parts at the micro-level. Such emergents are novel with regards to the individual parts of the system”. They also propose a working definition for self-organisation: “Self-organisation is a dynamical and adaptive process where systems acquire and maintain structure themselves, without external control” [2]. Both emergence and self-organisation are dynamic processes that arise over time, and both are robust, meaning that they are capable of surviving occasional failures of single elements. The only possibility to obtain a coherent behaviour at the macro-level is to let that behaviour arise and organise autonomously. Thus, combining both phenomena is a promising approach to engineer a coherent behaviour for complex systems.

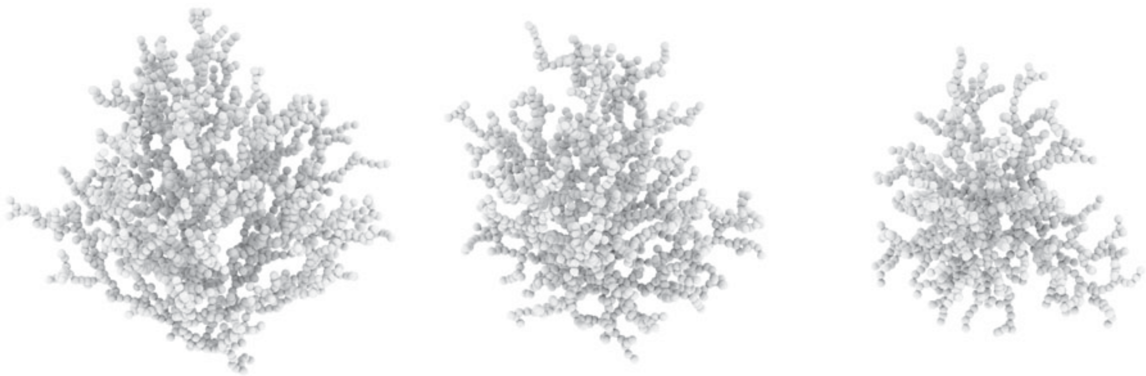
Furthermore, emergence should be adaptive in order to foster a system that is capable of self-organisation in a state of environmental flux, where the system responds to changing stimuli. Each element arises in relation to local conditions as well as factors that influence the entire system [3]. Adaptation can be viewed as a consequence of parallelism and iteration in a competitive environment with finite resources [4]. Behaviour is in this case subject to fitness, which determines a reaction for or against particular actions based on feedback mechanisms at all levels. It is particularly useful to consider adaptation in complex systems, because it allows the complex to evolve based on rules that can relate to practical applications.

Digital morphogenesis, or the generation of digital form, is capable of utilizing emergence and self-organisation as generative principles. However, in architecture, it is important not to regard the process of morphogenesis explicitly in terms of form generation: the geometric rigour and simulation capability of computational modelling can be deployed to integrate manufacturing constraints, assembly logics and material characteristics in the definition of material and construction systems [5]. In terms of adaptation, criteria for selection of the fittest can be developed that correspond to architectural requirements of performance [6]. Adaptive structures adapt to spontaneously changing environmental conditions while reacting to necessities resulting from the structure itself [7]. Therefore, computational morphogenesis is possible when complex systems incorporate the physical constraints of architecture and adapt to changing environmental conditions.

Complex spatial phenomena necessitate adaptive architectural design solutions. Physical space should evolve in response to shifting programmatic requirements and environmental stimuli through a process of structural adaptation. The aim of this research is to utilise an algorithmic, self-organising system in order to generate emergent, adaptive structures composed of mass-producible modular building components.

2. Diffusion-limited Aggregation

Diffusion-limited Aggregation (DLA) is a process of accretion over time which is observed in many natural systems, including electrodeposition, mineral deposits, snowflakes, dielectric breakdown (lightening paths), and even in living organisms (e.g. the growth pattern of some coral) [8]. Witten and Sander proposed a mathematical simulation of DLA: beginning with a single seed, a particle “walks” randomly from a distance until it reaches a position adjacent to the original seed, where it attaches to form a cluster. Subsequent particles appear at random distant points and walk randomly until they reach the developing cluster of aggregates [9]. The resulting cluster is a combination of many parts in defined relation to one another; therefore DLA is a self-organising system. Additionally, the coherent cluster at the macro-level dynamically arises from interactions between parts at the micro-level; therefore DLA is emergent. It also has the potential for infinite growth.



(Fig. 1) Left to right: gravity = -1.0; gravity = -0.5; gravity = 0

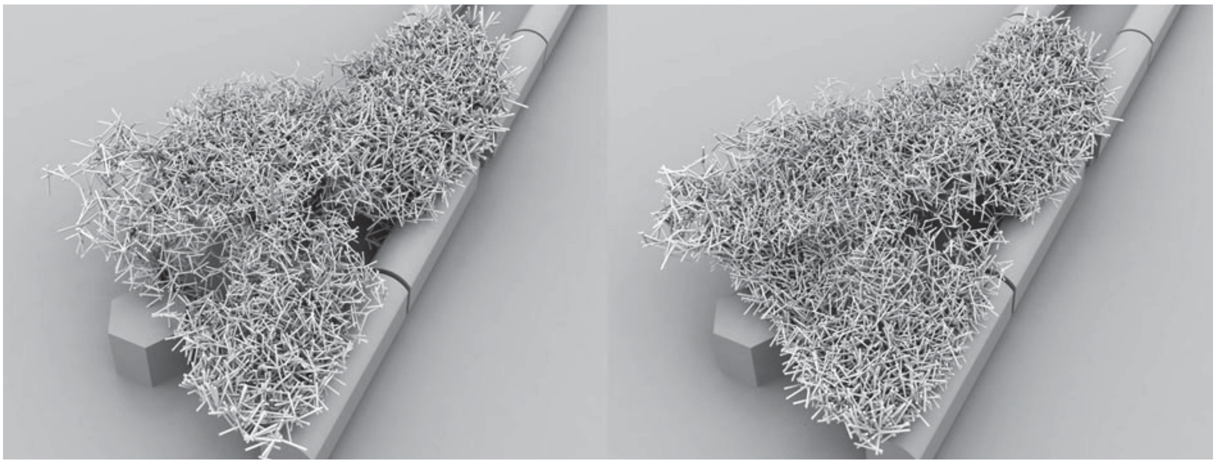
(Fig. 2) Left to right: stickiness = 1.0; stickiness = 0.5; stickiness = 0.1

The same probabilistic logic of Witten and Sander can be used to generate three-dimensional DLA through the implementation of a diffused particle system contained in toroidal space. Rather than walk, particles fly around at random velocities from random starting points at the boundary of the space, then attach to the cluster after breaching a specified threshold distance. Within this simulated environment, additional system parameters can be implemented to influence self-organisation. Gravity (Fig. 1) affects directional growth, creating clusters that appear to grow upward. Stickiness (Fig. 2) reduces the probability of a particle attaching to the cluster, which results in denser clusters.

3. Case Study

3.1 Digital Morphogenesis

First attempts toward architectural design based on DLA resulted in abstract instances of digital morphogenesis. Though not generated using material based computational methods, the resulting structures provide an initial glimpse into the power of DLA as a form generator and illuminate the problems that need to be addressed to implement an adaptive material system.



(Fig. 3) Emergent structures with identical boundaries and unique parametric settings

Several emergent structures were programmed to grow within predefined spatial boundaries (Fig. 3); all structures eluded prediction and culminated in a final “fit” iteration that best satisfies environmental and spatial requirements. System boundaries were manually modelled as a combination of physical-contextual boundaries (e.g. ground, walls, and doors requiring access) and desired spatial cavities for inhabitation (in this case, we performed “subtractive” architecture from a yet-to-be-generated structure that theoretically could have consumed the entire site). The aggregation distance threshold varies within the self-organising structure in a manner which supports perceived local structural requirements. This placement resulted in aggregates inheriting a specific size based on their proximity to chosen areas of the structure requiring more massive components (e.g. the base). The lack of a material system results in structures composed of proto-architectural components, all of which are unique in size and connection detail.

The algorithmic process allows for space-oriented mediation of the growth process as a means to impose top-down order onto an otherwise unpredictable self-organised system, yet there is also the option to influence growth via the parametric settings of the complex particle system and structure's encoded growth rules. Five settings were discovered to have the greatest impact on the outcome of each emergent structure: amount of flying particles, number of time steps, gravity, stickiness and threshold range of components. For clarification: time steps refer to the iterative, incremental movement of individual particles in the particle system (it is not practical to simulate a particle system in real time). Particle abundance and time step quantity mostly have to do with the efficiency of the algorithm: more particles means faster growth at the front end of the process, but slower growth as the structure matures; more time steps infer less particles and vice versa. Gravity value refers to the susceptibility of individual particles in the particle system to Earth's gravity. Reduced stickiness did not prove to be useful for architectural applications, as problems with density and intersection occur when a particle enters an already developed part of the structure and then attaches. The threshold distance for component aggregation is determined on the low end by a user-defined variable and on the high end by direct proximity to localities with greater normal stress. Because each manual setting can have a drastic effect on the fitness of an emergent structure, it was necessary to run many trials to find the right combination.

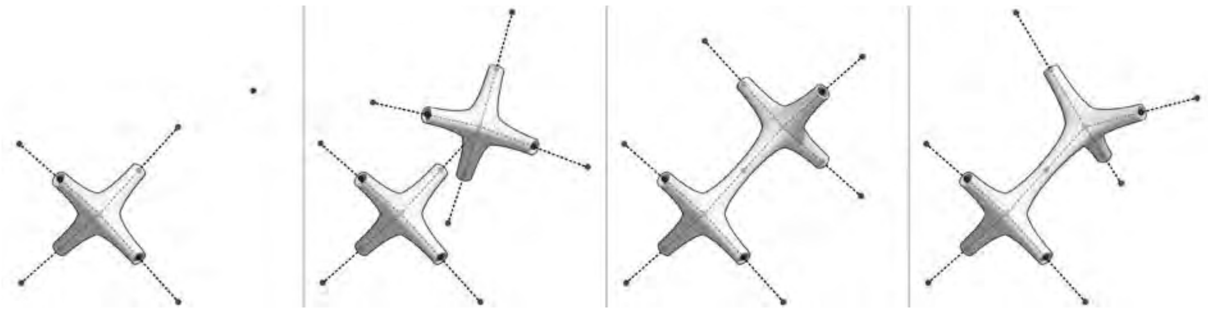
(Fig. 4) Interior perspective of generated structure with primitive geometry

Throughout the initial trials, primitive geometry was used to materialise the geometrical data culled from the algorithmic DLA simulation, more specifically aggregate coordinates and the connections between them (Fig. 4). Rather than constructing an architectural component directly at the point of each aggregate, an algorithmic function essentially converts generated information between aggregates into extended three-dimensional solid geometry (extension of the solid geometry was an early attempt to create tectonic relationships between the architectural components). Yet, this digital morphology fails to relate to real-world constructability due to the tendency toward unmediated topological intersection.

The initial algorithm, which bears a close resemblance to DLA, is capable of responding to environmental input in the process of generating emergent structures. However, its lack of a material system makes it impossible to generate a process for producing architecture in physical reality. The algorithm also does not take into account further expansion of the structure or reconfiguring building components for overall structural modification. Therefore, a modular material system (specifically composed of the same mass-produced module) must be generated parallel to localised geometry in order to produce adaptive algorithmic architecture.

3.2 Modular Material System

When a modular material system is generated alongside the emergent geometry of DLA, the algorithm implements computational morphogenesis. A series of localised modules oriented to the three-dimensional coordinates of each aggregate form a material system that can crystallise the structure in physical space. Taking advantage of industry standard CAD/CAM processes allows for precise and efficient prototyping of singular yet morphogenetically related components (as well their multitudinous connections). While CAM allows for mass-customisation and offers the potential for completely unique modular components, the goal in the development of this material system is to design a structure that can physically adapt to changing user demands and environmental conditions while undergoing only strictly controlled local transformations that facilitate the use of one mass-produced module.



(Fig. 5) Left to right: particle approaches existing module; new module appears at aggregate coordinates; new module is aligned to existing module; new module is rotated randomly to diversify local connections

The original model of DLA was inspired by the aggregation of metal particles observed through an electron microscope, and although the phenomenon occurs elsewhere in nature, it does not occur at the architectural scale. Challenges arise as the structure is magnified and used for the production of architecture, especially in the case of this modular system, because only one mass-produced module is eligible for aggregation. As opposed to the self-organisation of three-dimensional geometry in DLA, the computational logic of this material system introduces new rules for growth based on constructional constraints. Each identical module in the material system consists of four connection points and attaches to an existing module in the structure. Afterwards, the three free branches of each module become connection points for potential aggregation (Fig. 5). In this way, structural growth is strongly influenced by the morphology of the user-defined module.

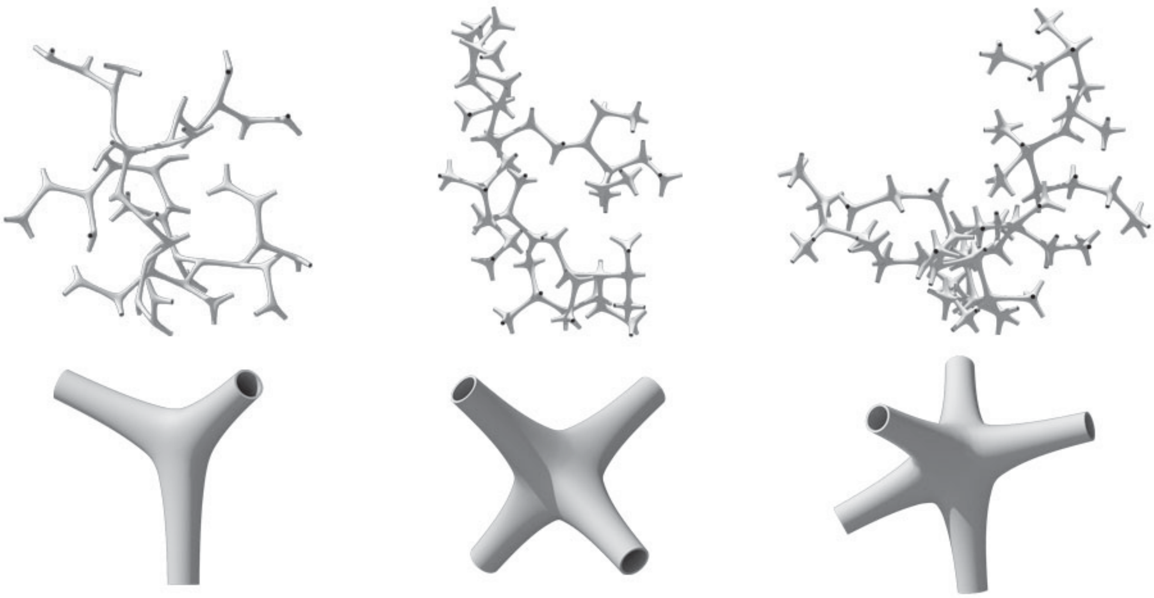
Material properties, manufacturing techniques and assembly logic of the material system must be considered in tandem with the overall generation of crystalline growth. A physical prototype has yet to be manufactured; therefore it is premature to decisively select a construction material and its most suitable manufacturing process. However, it is clear that the material must be light, formable, durable, and resistant to stress. Subsequent production techniques could potentially include thermoforming or injection moulding with a robotically-manufactured mould. Assembly can be carried out through a set of written or digital instructions or even by employing the precision of a robot.

Material system assembly logic, which was a priority in this research, is central to the performance of the generative algorithm based on a modular aggregate. The standardised nature of each module lends the material system to rapid adaptation. Each branch of the module is capable of attaching to all other uncoupled branches with six specific degrees of rotation. This allows a module to be removed from one portion of the structure and immediately reused in another. Modular components are able to correspond to a variety of connections at the micro-level in order to accommodate adaptation at the macro-level.

3.3 Design Solution

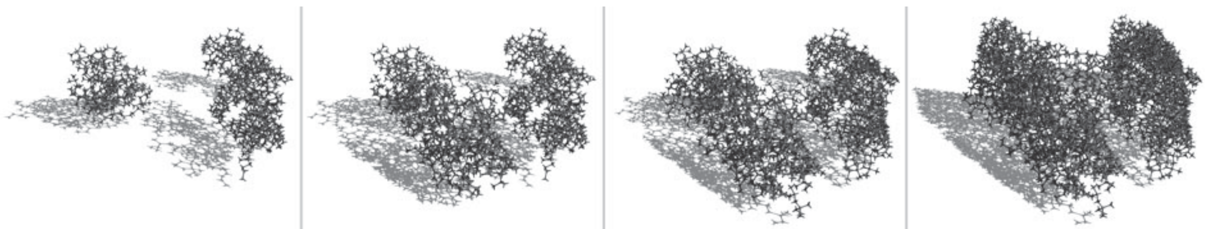
After critically defining the probability of growth based on information within the DLA system, architectural constraints can be incorporated to augment morphogenesis. Hensel and Menges posit: "Today the development of performative material systems, and in particular the technological advances of simulating their behavioural patterns of modulating and being modulated by the environment from the very early design phases on, enables us to further develop such modes of spatial organisation based on gradient conditions in interaction with physical thresholds" [10]. Adaptive material systems for architectural space begin to emerge when each aggregate in a generated DLA cluster is regarded as an architectural component. Through addition and subtraction of architectural "aggregates", the DLA based tectonic structure is able to grow as well as degenerate over time. It shapes aspired forms and architectural configurations. The structure can adapt to specific needs of the user (e.g. use) and shifting environmental conditions (e.g. daylighting) through a continuation of the DLA growth algorithm and subsequent rearrangement of components in physical space.

Converting the DLA algorithm from digital form generation into a computational design tool that automatically constructs a modular material system was an essential step toward making a meaningful design proposal. The design tool is similar to the original algorithm in that aggregates are bound and influenced by user-input geometry and parametric variables. Its self-organising growth process is no longer a direct representation of DLA due to modified aggregation logic; despite its diminished "authenticity," the algorithm has been effectively translated into a design tool for architectural morphogenesis. Additionally, the tool is adaptive: it is capable of restarting growth on existing constructions as well as intelligently subtracting modules based on changing performance criteria over time.



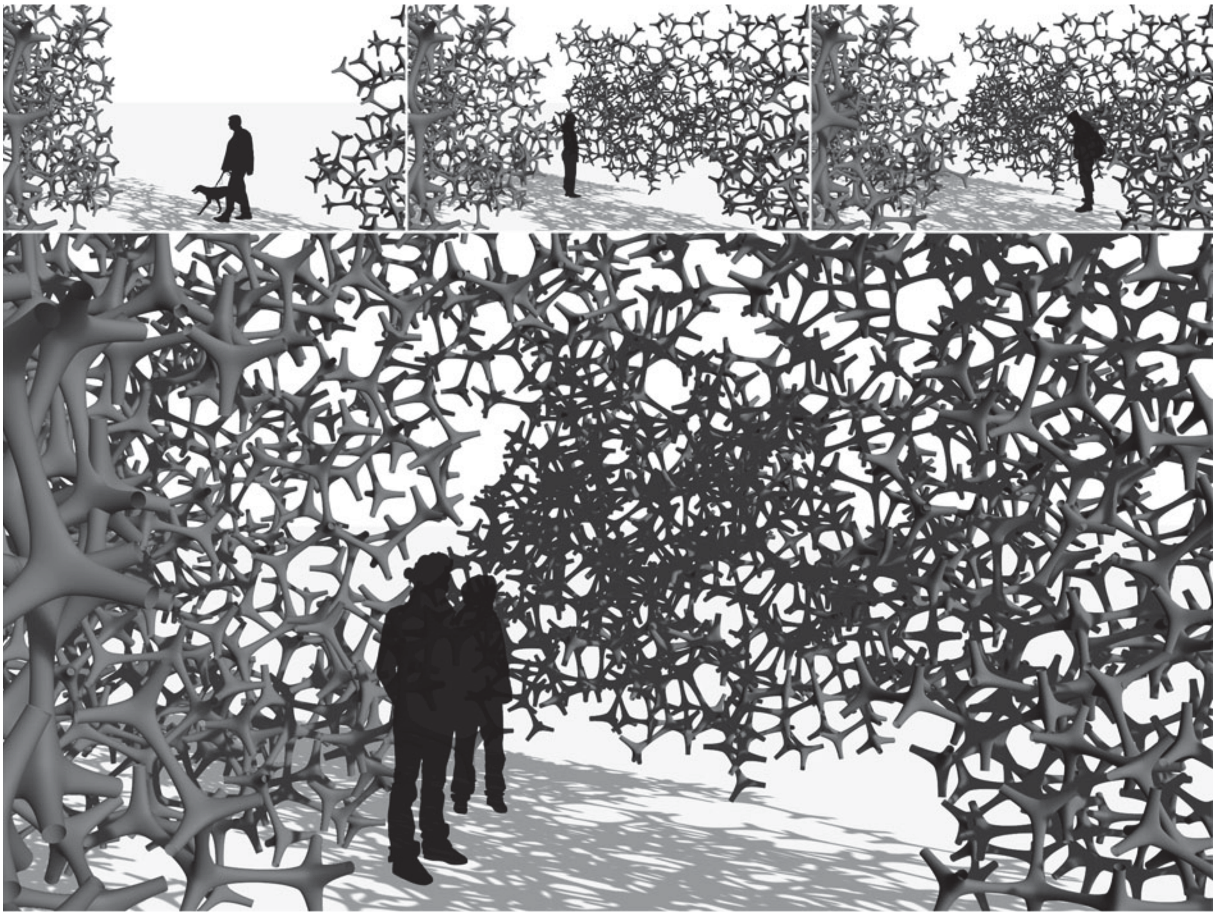
(Fig. 6): Module variations with three, four, and five connection points

First of all, the design tool is capable of computing an emergent structure that relates directly to a physical construction based on a modular material system. The construction is generated in a bottom-up process based on a user-input module with specific connection joint details for subsequent aggregation. The tool begins by identifying user-defined seeds for the emergent structure and places the first modules at their coordinates. Further local interactions occur when uncoupled branch termini lie within the defined spatial boundaries for aggregation. Self-organisation in design tool, the process for which was originally inspired by DLA, maintains its natural capacity for emergence. Local relationships between repeated modules of with varying connection capabilities continue to give rise to unpredictable behaviour in the overall composition (Fig. 6). There is a positive relationship between the amount of connection points in the module and the density of the structure overall.



(Fig. 7): Growth of structure over time based on circulation patterns and shading

As a means for adaptation, the computational model can be reloaded and the design tool initiated yet again. Growth is continued with new parameters responding to environmental conditions, for example thermodynamics, spatial assimilation and daylighting as well as performance criteria, such as structural optimisation and use (Fig. 7). Modules that are determined to be unnecessary or “unfit” by the tool are removed, while new modules are added and catalogued for implementation in the physical construction. Because the morphology of the module is consistent throughout the process, it is versatile. Formerly unfit modules can be again added to the structure as a way to reduce the ecological and economic impact of producing new modules. Architectural space can be reconfigured over time with significant ease following construction rules generated by the digital model.



(Fig. 8): Interior perspectives exhibiting structural adaptation and spatial nuance

The resulting construction, while in its current theoretical state not yet realised as a physical prototype, is capable of providing a series of environmental modulations based on desired affects (many of which can be simulated). Because the design tool was not envisioned based on traditional design methodologies, the construction itself is capable of producing architectural spaces with emergent experiential qualities. Unforeseen characteristics of the generated construction contribute to a gradient space between what is typically understood as outside and inside (Fig. 8); the modular material system allows structures to grow in a generative way with unexpected outcomes that carry the potential for unimagined uses.

Conclusion

The complex DLA based structure presented in this paper exploits design tools readily available in computational design, namely self-organisation and emergence as means to produce realisable constructions. Through this design process, the structure is able to adapt over time to a range of stimuli, and with the implementation of a modular material system, the design tool produces not only digital geometry but also offers the potential for production and assembly at the architectural scale. Perhaps most importantly, the module (which corresponds to the aggregate in the mathematical model of DLA) is repeated throughout the structure and can be mass produced as well as reused in subsequent constructions.

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