Swarm Materiality

A multi-agent approach to stress driven material organization

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Abstract. *This paper sets out to introduce and explore a computational tool, thus a methodological framework, for simulating stress driven material growth and organization by employing a multi-agent system based in swarm intelligence algorithms. It consists of an ongoing investigation that underlies the intention for the material system to be perceived as design itself. The algorithm, developed in the programming language Processing, is operating in a bottom-up manner where components and data flows are self-organized into design outputs. An evaluation process, via testing on different design cases, is providing a coherent understanding on the system's capacity to address an acceptable, within the "state-of-the-art" context, solution to material optimization and innovative form-finding. The analysis of the exported data is followed by a possible reconfiguration of the algorithm's structure and further development by introducing new elements.*
Keywords. *Swarm-intelligence; stress; material-organization; biomimetics; processing.*

MATERIAL AS DESIGN

Computational design tools have amplified architects capacities on both conceptual and technical levels in terms of manipulating complex geometrical configurations and introducing pioneering design initiatives. A post-rationalization process is however, essential in the majority of the contemporary design cases in order to resolve problems emerging from the translation of digital information to physical materialized objects. This dualism from digital to physical, from bits to atoms (Negroponte 1995) and vice versa, has introduced a great number of studies towards the lossless realization of digital design or its optimized implementation. Recent investigations on material systems science, Computer Aided Manufacturing and Evolutionary Developmental Biology, provide the foundations for a forthcoming concrete articulation of the "digital design – fabricated design" system.

In this context, the main objective of this research is to introduce and explore a computational tool, thus a methodological framework, for simulating stress driven material growth and organization by employing a multi-agent generative system based in swarm intelligence algorithms. The fibrous intrinsic characteristics of this dynamic performative system, following the agents' trails, operate by adapting to certain stimuli while exchanging information in a reciprocal manner with the environment's spatial qualities, fulfilling multiple tasks and consequently converging into a local optimal scenario. Structural information in combination to morphological and topological data become, along with the multi- agent system's behaviour, the driving forces in a bottom-up approach where data flows and components are self-organized into design outputs. This ongoing investigation underlies the intention for the material system to be perceived as design itself. Therefore is intended to bridge the gap between digital and fabricated matter and through its adaptive virtues and its force-energy morphology evolving (Thompson 1961), to progress towards an enhanced conversion of design and material growth, as this appears in natural systems.

The proposed algorithm, developed in the java-based programming language Processing, is explored via testing on different design cases, offering a coherent understanding on how the various elements perform and a critical evaluation of the system's capacity to produce an acceptable, within the "state-of-the-art" context, solution to material growth optimization and creative form-finding. In addition, these experimentations outline the intriguing elements of the generative multi-agent system, forming its implementation, while at the same time revealing its limitations. The analysis and evaluation, leads to possible reconfiguration of the algorithm's methodological structure and further development of the concepts describing it, by introducing new elements and reinforcing the existing.

BACKGROUND

A multidisciplinary approach

The examined algorithmic system utilizes knowledge and apparatus from the fields of biomimetics, material systems science, engineering and computational science to form a rational and hierarchically articulated methodology. Nature is providing a tremendous amount of information implemented into these scientific fields, assisting contemporary investigations that vary from the analysis of the human body's structural element: bone's micro-mechanical configuration (Huiskes 2000), to the effect of the micro-fibril orientation into plant growth. Research conducted on fibre composite materials, biomechanical load bearing, plant growth and structural optimization procedures, is implemented within the algorithm's structure and realized through the dynamic computational model of the collective behaviour ordered swarms, leading to an interdisciplinary approach on creative design through optimized material distribution.

Figure 1
Material as design: rendered still of the algorithm.

Multi-agent synthesis strategies

"Swarm Matter" by Kokkugia is a morphogenetic research process within the software development framework that investigates the generation of ornamental geometries through swarm intelligence based formations and emergent patterns [1]. This exploration is analogous to the presented algorithmic process in the implementation of a multi-agent system operating as a form finding module. However it diverges from it radically in the methodology by which, contextual data are incorporated into the process and by the nature of the data itself, which is not limited to the inherent interaction within the agent system.

Structural information as design initiative

Research conducted by Michalatos P. and Kaijima S. (2007) employs structural information as a design element. Specifically, the case study of the "Land Securities Bridge" is examining procedures on optimizing a preliminary design intention through the method of densification, while at the same time organizing the data operating on the design as fields of values. A related approach is integrated in the proposed system through the densification of the fibre matrix.

A different research case investigates adaptive growth through fibre composites, operating on the specific design scenario of a pedestrian bridge, using the Tow Fibre Steering fabrication method on a field of uniform mechanical stress (Doumpioti 2008). The Computer Aided Internal Optimization (CAIO) method is exploited (Mattheck 1998), where fibres are aligned with the stress force flows mimicking plant growth. The intrinsic characteristics of fibres are engaged in the presented system in an equivalent method.

Those investigations have provided inspiration and technical knowledge regarding the notions examined in this paper. The implemented formal and practical systems are reinforced by the emergent situations of the multi-agent algorithm. Material optimization routines are engaging interaction and adaptation, in addition to the inspired morphogenetic and form-finding methodologies as a combination of reactive and informative systems. Consequently, this research explores the dynamic characteristics of multi-performative systems implemented into information based design processes and attempts to evaluate it.

SWARM MATERIALITY: ALGORITHM'S STRUCTURE

Inputs to outputs

The structure of the algorithm is expressed as a linear process constantly resulting to emergent outputs. This input to output procedure introduces a set of dynamically defined routines, both in terms of design-production, but also in relation to the optimization of the results. Being characterized as an information-based adaptive system, the algorithmic framework is powered by a set of inputs that vary in their nature and by the effect they address on the operational attributes of the system. The totality of input values can be categorized as:

1. User defined inputs: Initial morphology examined, seeds, agent system steering values.
2. Analytical inputs: F.E.M derived vector-field.
3. Combinatorial inputs: Porosity field depending on the sun's position.

User defined inputs can be altered on demand. Different geometries suggest alternative design scenarios affecting both the analytical and the combinatorial inputs which intrinsically relate directly to the examined morphological configuration. Specifi-

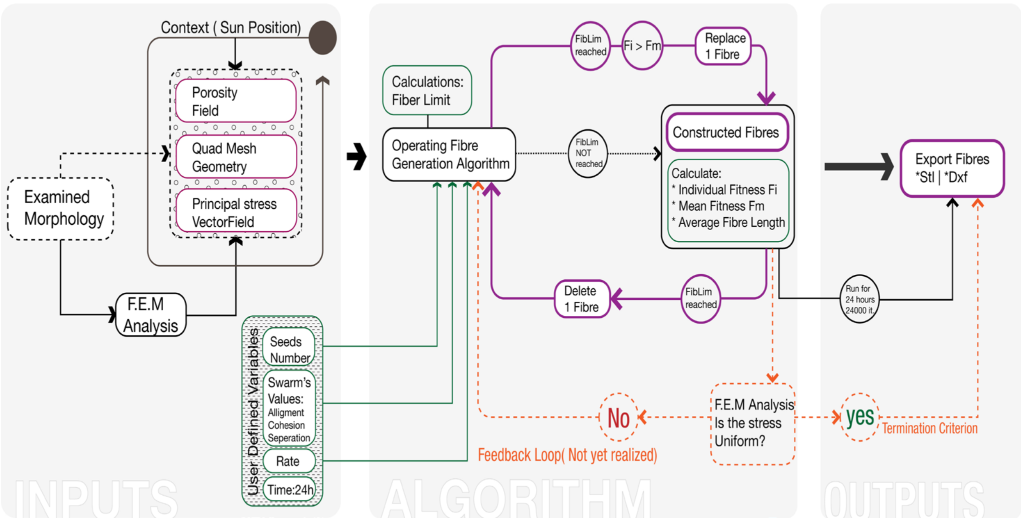

Figure 2
Schematic overview of the algorithm: inputs to outputs.

cally, the emergent result of the system is possible to differentiate greatly when the multi-agent system's steering values are changing, or if the quantity and the position of the seeds, are altered. In contrast to the randomly placed seeds, the initially user defined steering values can be transformed on a local level due to the adapting virtues of the system.

On the other hand, the outputs of the system consist in their majority of data sets provided thought-out the implementation of the algorithmic process in evenly distributed time periods, in favor of a more comprehensive evaluation. Stills of the running algorithm and text formatted sets, recording the various elements of the scheme at incremental intervals, are supportive to the main product of the system, which is comprised to dxf and stl exports of the fibrous design.

Data driven design

The algorithm implements a swarm intelligence dynamically defined routine based on the flocking boids procedural model by Craig Reynolds [2], followed by the numerically defined variables of alignment, cohesion and separation that characterize the population of the flocking agents. This fibre producing system performs on a basis of two adaptation factors, each of which is addressing a different weighted effect to the final outcome. The primary adaptation criterion is the principal stress value set adopted as a vector-field, or more precisely as voxel data field, derived by Finite Element Method analysis of the examined geometry using structural engineering software such as Solidworks™ and Oasys GSA™. A text file containing the principal stress data is translated to modules of information within the algorithm. Each module contains a numerical stress value, a topological data set, and a vector in relation to its neighboring modules-voxels. The FEM evaluation is performed using polymer as the material for the study, providing at the same time that the structure is self-supported.

The second adaptation mechanism emerges from the three-dimensional environment of the program's interface. This interface integrates a sun system utility that operates by calculating the angle by which sun rays collide to the geometry's domain, organizing a new data-field operating on a second level of hierarchy following the initial FEM adaptation. This process arranges different porosity levels on the overall geometry resulting in a plethora of anisotropic material design configurations, thus can be proved extremely useful in architectural design cases. On the other hand it may lack functional and conceptual reasoning in object-based studies. On these grounds, each adaptation factor can perform independently or in combination, with the stress driven growth to occupy the first level of importance within the system.

Fibre generation

The fibre generating algorithm performs on a logic that exploits the multi-agent system's characteristics. Each agent member of the swarm population navigates on the UV surface domain of the exam-

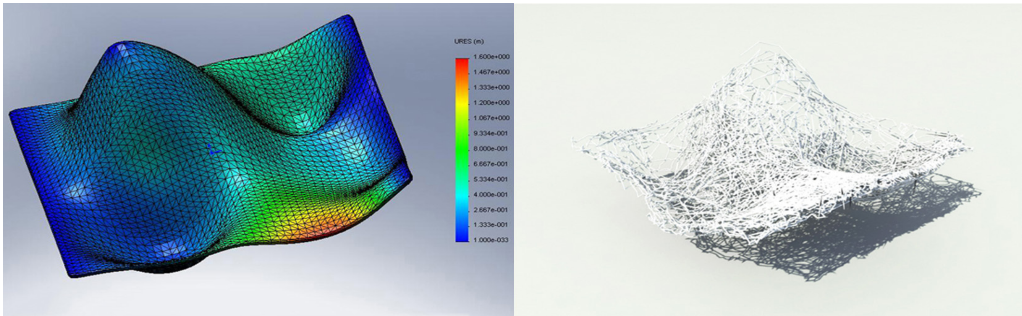

Figure 3
Finite Element Analysis on a free form surface and its fibrous implementation.

ined case study, interacting simultaneously with other members of the population while informed by the adaptation mechanisms. The seeds, the areas where the fibre growth commences, are randomly placed on the morphology while their quantity can be redefined as the algorithm is running. In a simplified scenario, each fibre agent tries to navigate through a larger number of high stress areas in the data vector-field, while continuously trying to avoid others where the second adaptation mechanism of the porosity data field is operating, hence agents tend not to approach areas with large porosity values. Each agent of the system is defined by a steering vector. When the agent is within the operating area of a large stress value voxel of the field, another vector with direction towards to the stress point gets added to the steering vector, moving the agent through this high stress zone. The added vector is not however capable of keeping the agent on a constant looping course inside the stress area. In addition, while navigating inside this area, the steering values of the agent members affected are instantly altered. In particular, the alignment value increases along with the cohesion, as the separation value gets narrowed down to keep agents as close as possible, therefore achieving greater fibre densities. Those values return back to the user defined ones when the agent exits the field.

The sun position depended porosity layer of adaptation runs on a similar methodology, by adding vectors towards or in reverse directions from the high or low porosity areas. However in this case, the initial steering values are not affected by any means. Where sun rays are more direct the algorithm tends to reinforce its structure while in other cases receiving oblique illumination, material is organized in a diluted mode.

The methodology of re-orienting fibres in highly stressed areas thus depositing more material is correlated to the Soft Kill Option (SKO) and is the same technique that nature uses to advance growth (Mattheck 1998). However, it is this research's intention not to get attached to a specific methodology but to advance in a combination of theories and optimization routines implemented and documented in this context.

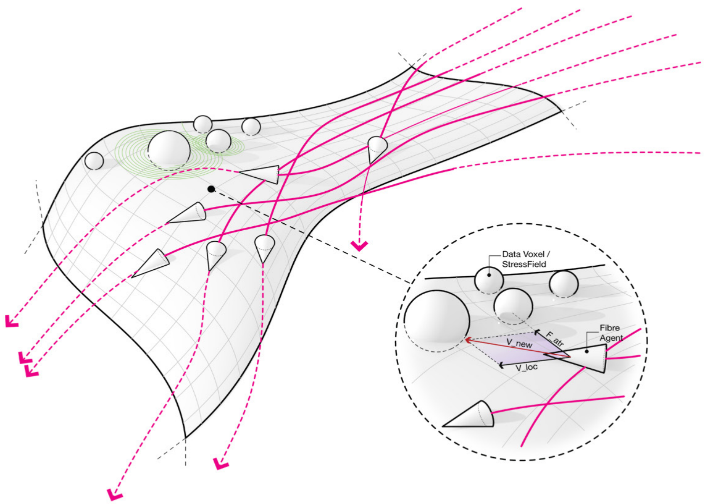

Figure 4
Schematic diagram of the stress adapting fibre generating agents.

Finally, the concluding element of the multi-agent system is a constrain factor to prevent the overdesign of the structure. The algorithm iterates at the previously documented state, generating a moderately large amount of fibres until a certain threshold is met. This threshold is dependent on the geometry examined and limits the number of fibres integrated in the final material configuration according to the fibre matrix ratio used in composites, provided via an approximation of this equation (Ashby and Jones, 1986).

$$EcL = \{Vf / Ef + (1-Vf)/Em\}^{-1} \quad (1)$$

where Vf is the volume fraction of fibres, and Ef, Em are Young's modulus for fibres and matrixes in Gpa.

Evaluation Process

From the total number of fibers generated in the algorithmic process only a few are converted into material design. Until the fibre limit is met the algorithm realizes to fibres only those multi-agent paths that are routed through more than ten high stress areas of the data field. This limitation could result to a highly differentiated sum of fibres, that may or may not, combine the fullest of the systems capacities. However, whilst the limit criterion is active, the algorithm evaluates recursively each member of the fibre population and assigns a double numerical value to it. This number is provided by the following fitness equation.

$$Fitness = \frac{\sum_{i=0}^{n} Spi*Dpi}{(n+1)} * \frac{(k+1)}{\sum_{j=0}^{k} Atj*Daj} \quad (2)$$

where n is the number of stress vectors, k is the number of porosity attractors, Sp is the stress value of the vector, Dp is the distance of the fibre to the stress vector, At is the value of the attractor and Da is the distance from the attractor.

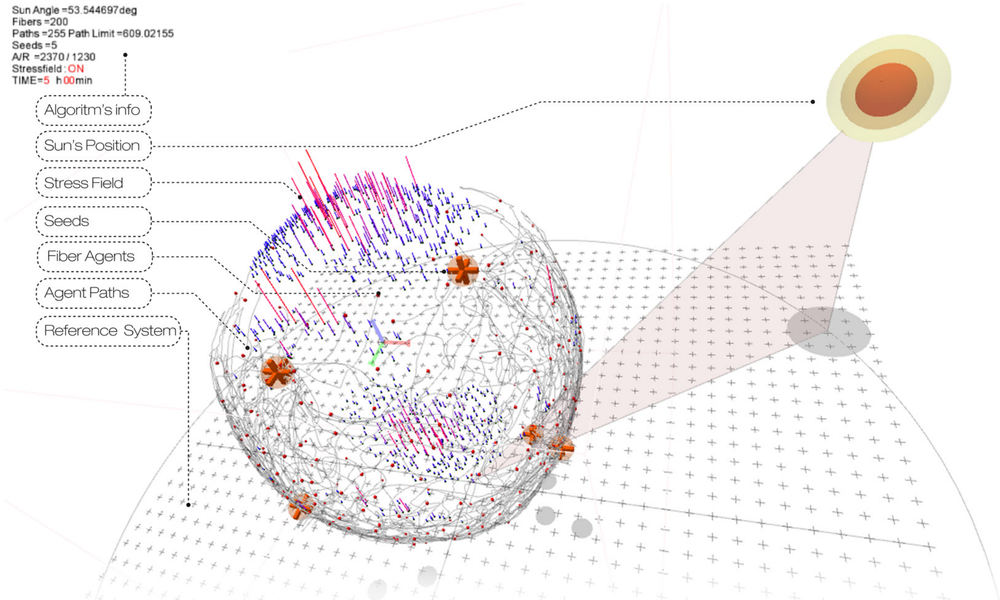

Figure 5
Explanatory snapshot of the performing algorithm.

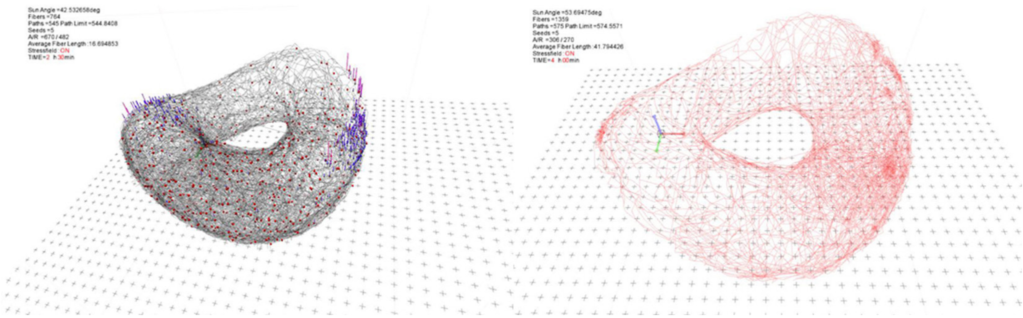

Figure 6
Stills displaying the performing agents (dark colored) and the constructed fibres (red colored).

As the algorithm iterates, it deletes a single fibre from the population and replaces it with another from the ongoing operating fibre agents, which must carry a fitness value larger than the population's average. The system runs for 2400 iterations at this mode until is terminated. By this methodology, it achieves a steadily advancing and controlled performance optimization, resulting to the material optimization of the final design product. In this aspect, the previously mentioned SKO methodology is reinforced by a selective process that categorizes fibres not only by the necessity of lying in high stress areas but by efficiency in combining the best achieved results.

A more reliable approach that has not yet been realized in the context of this research is the implementation of a continuous F.E.M evaluation for the fibre population, and via this feedback loop, to provide a sufficient termination criterion for the process. This methodology relates to the Computer Aided Optimization method where a biological shape is consistent with the uniform stress axiom (Mattheck 1998). In other words, when the results of the analysis indicate a uniform stress throughout the examined geometry the algorithm will terminate resulting to local optimal solutions.

TESTING AND RESULTS

The presented computational system is evaluated through testing on ten different geometrical configurations, such as spherical cubes, knots and teapots, in addition to variations by altering its user defined, agent or contextual, parameters. The nature of the data accumulated varies from, text files and vector graphics images, to stereolithography models. Certain output elements have been rendered of great importance during the experiments. The Average Fibre Length (AFL) is a critical measure for the evaluation process. In most cases the AFL steadily converges to a certain value, providing the optimal fibre length for the specific design case. However the topological configuration of the fibre matrix is unique each time, due to the dynamic characteristics of the swarm based multi-agent system.

The number of seeds affects greatly the overall design. Smaller number of seeds suggests greater

Figure 7
Rendered stills of the teapot geometry at different iterations of the algorithm.

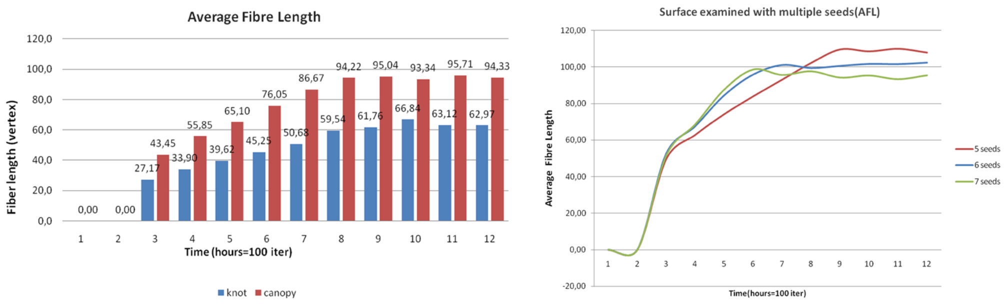

Figure 8
Charts displaying the Average Fibre Length for different geometries and number of seeds.

AFL values and vice versa, being at the same time highly depended on the morphology investigated. Furthermore, the system converges faster into possible solutions when more seeds are defined, underlying the danger of a latent overdesign, which can't be controlled at this state. The multi-agent steering values can also alter the design output. For instance smaller separation value, provides highly routed fibers, thus for the purpose of this research these values were kept at a neutral level in all experiments. Finally, the porosity data field has introduced different transparency levels and highly anisotropic characteristics on the overall geometry, again with a vigilantly selected value data set to avoid overdesign at certain areas.

AN ARCHITECTURAL CASE STUDY

An implementation in a large scale conceptual project consisting of a multi-story building development [3] is examined by the application of the generative process in a recursive fashion throughout the design. The overall morphology of the building

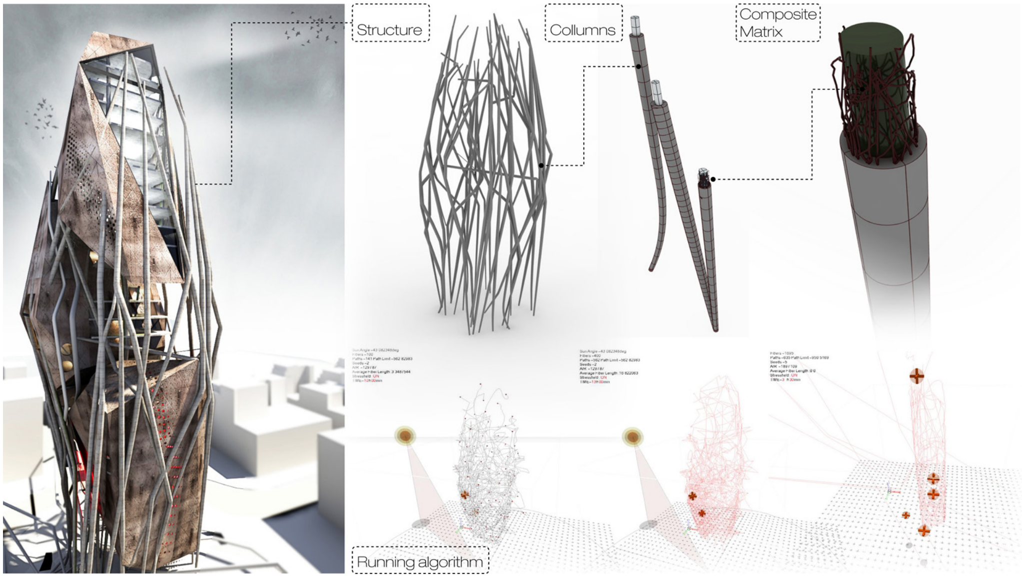

Figure 9
Architectural design case-study displaying a recursive implementation of the presented algorithm.

was analyzed by the computational system providing the structural elements of the design, which were then re-designed by the same algorithm in the micro-scale level. The complex columnar elements have been evaluated and addressed as a composite of a common used matrix, such as concrete, reinforced by the fibrous assembly. Although being only an experimental implementation, the existence of several integration possibilities that can be suggested in analogous contextual frameworks, is identified.

CONCLUSIONS

When considering material as design, the presented system has been proved successful in terms of replicating material growth and arrangement while achieving a stress adaptive character. It diverges from the other accessible methodologies principally in regard to the implementation of the multi-agent fibre mechanism, and its inherent capability to evaluate multiple design scenarios, converging to a local fittest. This process is primarily defined in natural systems that initially grow the material and then optimize it by re-deposition. The intrinsic incapacity of the system to provide global optima, similar to other optimization methods such as Genetic Algorithms can be addressed as an advantage in terms of design pluralism. Furthermore, the running algorithm has been proved an interesting spectacle, specifically during the evaluation process when the replacement of fibres appears, converging to creative designs.

Finally, the experiments have indicated a significant amount of issues that have to be attended, with primary aim, the implementation of a termination criterion via a FEM analysis feedback loop, capable of reinforcing the evaluative character of the algorithm and advance its optimization characteristics.

REFERENCES

Ashby, M and Jones, D 1986, *Engineering materials 2-An introduction to microstructures, processing and design*, Butterworth-Heinemann, Oxford.

Burgert, I 2006, 'Exploring the Micromechanical Design of Plant Cell Walls', *American Journal of Botany 93(10)*, Potsdam, Germany, pp. 1391–1401.

Doumpioti, C 2008, 'Adaptive Growth of Fibre Composite Structures', *Silicon + Skin: Biological Processes and Computation, Proceedings of the 28th Annual Conference of the A.C.A.D.I.A*, Minneapolis, United States, pp. 300-307.

Fratzl, P 2007, 'Biomimetic materials research: what can we really learn from nature's structural materials? ', *Journal of the Royal Society 4*, Potsdam, Germany, pp. 637–642.

Holland, J.H 1996, *Hidden Order: How Adaptation Builds Complexity*, Perseus Books, Cambridge.

Huiskes, R 2000, 'If bone is the answer, then what is the question', *Journal of Anatomy* 197, Netherlands, pp. 145–156.

Jeronimidis, G 2000, *Structural Biological Materials, Design and Structure - Property Relationships*, Pergamon, Amsterdam.

Mattheck, C 1998, *Design in nature: Learning from Trees*, Springer-Verlag, Berlin.

Michalatos, P and Kaijima, S 2007, 'Structural Information as Material for Design', *Expanding Bodies: Art • Cities • Environment, Proceedings of the 27th Annual Conference of the A.C.A.D.I.A*, Halifax, Nova Scotia, pp. 84-95.

Negroponte, N 1995, *Being Digital*, Vintage Books, New York.

Thompson, D, W 1961, *On Growth and Form*, Cambridge University Press, Cambridge.

[1] www.kokkugia.com

[2] www.red3d.com

[3] www.digitalsubstance.wordpress.com