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Prototaxites stellaviatori: a fungal growth simulation model for Mycelium-Based Composites education in applied arts.

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ABSTRACT: The increasing experimental investigations of Mycelium-Based Composites (MBC) in design and architecture necessitate efforts from pedagogues to find ways to transmit knowledge and support regarding the guiding principles of mycology so as to empower students in their investigations and study. The adoption of MBC craft in arts and applied arts offers much potential in extending the space of material semiotics as it is often accompanied by several theoretical and systemic interests, such as the urge to adopt alternative ontologies of nature or implementing thoroughly sustainability in the economy. To support these critical reflections and exploring novel formal expressions we have developed a stochastic simulation model of fungal colonisation for design education and research in MBC. In this paper we present the conceptual and technical framework guiding the model's development with specific focus on its role as a pedagogical instrument. We report on its pedagogical impact based on a students survey and their productions.

1 INTRODUCTION

Mycelium-Based Composites (MBC) represent a class of materials that has only recently come to be used in design and engineering. Inspired by early XXth century method of fungal strain transfer by lignocellulosic solid-state fermentation (SSF) (Duggar 1905), the use of this craft in design was popularised amongst others thanks to the 2009 Mycotecture works of Philip Ross (Ross 2016). Since then, a wealth of design and architecture projects have been revealed, while the material semiotics of MBC is still young and being established. The cultivation principle of MBC relies on the saprotrophic lifestyle of ligninolytic fungi, or wood-rot activity, and consists in having wet lignocellulosic substrate colonised by a mycelium. Such mix is typically incubated at a temperature fit for optimal enzymatic activity for a few days, that is until the substrate has been colonised by the fungus according to the design intent. The colonisation speed and incubation duration vary depending on strains, substrates, and design objectives. This simple and frugal process of composite craft actually reflects a wide-ranging design space and complexity because it can be implemented with a wide variety of substrates, both in terms of chemical profiles and geometries, and a range of basidiomycota. Furthermore, the spread of MBC craft is often accompanied by theoretical and systemic interests, such as the urge to adopt alternative ontologies of nature, or implementing thoroughly sustainability and social justice in the economy, stakes that need fine integrating in applied arts educational programs.

The increasing experimental investigations of MBC in applied arts necessitates efforts from pedagogues to find ways to introduce students to the guiding principles of mycology. Such a knowledge set is complex in nature as it relies on an advanced biochemistry literacy that design students are not usually exposed to during the course of their studies. Thus, they must be able to grasp tacit knowledge — knowledge that cannot be formalised — of MBC crafting without tackling the full explicit knowledge set available in mycology. Furthermore, this craft must then be integrated with

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design expertise. Such design expertise is also relying on tacit knowledge and is taught accordingly by resorting to design pedagogy, in particular via studio works. The pedagogy presented here relies on the articulation of these two sets of tacit knowledge by having the students venture into physical experimentation with MBC. The pedagogical proposal has been assessed with the help of the Socialisation-Externalisation-Combination-Internalisation (SECI) model (Nonaka, Toyama, and Konno 2000).

In this paper we present the framework guiding the development of a simulation model, named *Prototaxites stellaviatori*, with specific focus on its role as a pedagogical instrument. Accordingly, we evaluate its impact based on student interviews and material evidence produced during an MBC teaching workshop in September 2020 at the Royal Danish Academy. The goal of this workshop was for students to quickly achieve design agency in material proposition (internal characteristics based on constituents and composition) and application (conventional architectural design proposition), to gain an appreciation of underlying mechanisms of the simulation model, to explore modes of manipulating the plugin to achieve design intent, and, through the process, to develop critical thinking on the design implications of designing and cultivating materials implying living non-humans. The evaluation of the pedagogical impact examines the architectural and technical strategies developed by the students as well as the semantics they resorted to in describing them, seeking to understand the knowledge conversions at play. Finally, we conclude on the students appropriation of the role of simulation models and MBC conceptual framework with regards to somatic tacit knowledge — knowledge relative to corporeal perceptions (Collins 2010). A teaching support document is made available in a public repository along with documentation of student explorations and design outcomes (Rigobello et al. 2021).

2 TEACHING CONTEXT

2.1 *Pedagogical context*

Numerous post-structuralist and new materialist writings have been advocating for the adoption of a relational Kantian aesthetics based on affect as a counter discourse to modernist rationalism (Rigobello and Gaudillière-Jami 2021; Lowenhaupt Tsing 2015). While learning MBC cultivation methods is part of our workshop syllabus, it is critical that fungi is not only presented as a mere technique but in a manner that allows students to develop their tacit knowledge of the fungal life with the full extent of their corporeal sensibilities. Building upon an applied arts pedagogy that recognises the centrality of synthesis, analogy, and craft practice in the design expertise (Schön 1985), our drive towards conveying theoretical controversies finds a favourable ground, and is expected to echo and augment prior cenesthesic intuition in students — the blend of various bodily sensations producing a tacit awareness of being in a particular physical condition. As MBC cultivation is being democratised with commercially available kits for individuals along with a profusion of do-it-yourself workshops, and thanks to the process being frugal in not requiring expensive equipment or advanced skills to reach a satisfactory result, we can witness that a detailed understanding of the biochemical processes at play is not mandatory for using MBC as a design medium, thereby rendering it very accessible and inclusive.

The architectural design master programme Computation in Architecture offers a computational design and digital fabrication-oriented program hosted at the Royal Danish Academy. At the beginning of each academic year, both fourth and fifth year students are grouped for a series of introductory workshops designed to immerse them in materially-focused computational design logics that are thematically linked to active research projects led by the Centre for Information Technology and Architecture (CITA). Through this research-led teaching, students are exposed to a coherent set of questions, theoretical positions, concepts, methodologies and state-of-the-art materially oriented design and production workflows for them to anchor their subsequent individual semester and thesis projects. Fourth year students rarely have prior experience with computational design or biodesign. The workshop forming the focus for this paper, consisted of a preliminary two-week session called *Shaping Growth: composing material heterogeneity* that had the following objectives: producing a cast for forming and growing a mycelium-based composite, composing the substrate such as combining bulk material together with specifically orientated fibres, being introduced to methods of sensing and real-time monitoring of living materials, together with data-collection and querying, engaging in digital modelling of physical artefacts and be shown how to situate them within an extrinsic modelling environment allowing to generate

artefact performance data from environmental simulation. A second two-week session called *Liquid Modelling: navigation beyond vision* was held directly after the previous one. Its objectives are formulated as learning hypothesis in section 3.3.
A supporting document synthesising the fundamentals of MBC craft and of the functioning of the *P. stellaviatori* plugin was provided to the students at the beginning of the Liquid Modelling workshop. This document is made available in the same public repository as the documentation of student work and results (Rigobello et al. 2021). The workshop sessions embedded a day of lectures and tutorials each, the remaining of the time was dedicated to group work.

2.2 *The Rhinoceros 3D - Grasshopper environment*

Grasshopper is a visual programming environment within the Rhinoceros modeller. It uses visual programming, a particularly popular method of learning programming for novices, as studies of such techniques as used not only in the computational field but also elsewhere point out (Celani and Vaz 2012). Grasshopper is a didactic environment thanks to its online supporting community. Many observers associate this environment with what Eric Raymond calls a *bazaar*: a software environment that emerges through contributions from a larger, open community. Raymond crafted the term in opposition to *cathedrals* traditional software environments, referring to larger applications developed by a small group in a closed environment (Raymond 2001). Because visual programming facilitates abstraction and the acquisition of logic, its learning curve is meant to be less steep than for command line programming. However, the curve quickly reaches a plateau, trapping users in a narrower range of possibilities. Visual programming therefore poses a challenge in terms of upgrading users' skills (Celani and Vaz 2012; Aish and Mendoza 2016).
Despite its limits, Grasshopper was selected for the implementation of the *P. stellaviatori* model as it allows for articulating with other pedagogical methods and therefore enables the coexistence of a variety of learning strategies. One of the main issues in education in the computational field in architecture is indeed the need for the combination of several learning goals across multiple fields. While the students are expected to learn programming skills, they are also primarily in a design course and must be able to develop skills relating to the acquisition of architectural expertise. In our case, the students are expected to experiment with mycelium and learn cultivation processes along with developing critical thinking regarding simulation activities in design. We thus consider Grasshopper to provide a particularly suited platform for us to develop a multiscalar pedagogy that relies on three pillars: programming, designing, and cultivating. We resort to Grasshopper to enable the interfacing between the *P. stellaviatori* model and solar radiation simulation, and to articulate the reinforcement of the connection between programming and physical experimentation to support the acquisition of somatic tacit knowledge.

3 METHODS

3.1 *The P. stellaviatori model*

A fungal growth simulation model was designed as the *P. stellaviatori* Grasshopper plugin. Fungal colonisation is driven by a wealth of factors including moisture qualities and dynamics in the substrate, the fitness of the substrate chemical profile to fungal species enzyme array, the aeration of the substrate during fermentation, the UV stress, the presence of other microorganisms, and the protocol care by the producing person. The simulation model focuses on integrating evaporation and capillarity as prime vectors for predicting fungal colonisation, because the presence of capillary water in SSF substrate is a prerequisite to allow extracellular transport of metabolites in fungi, and to establish osmotic potential for allowing turgor pressure and subsequent hyphal growth (Money 1995). In timber, moisture can exist as bound water within cell walls below fibre saturation point (FSP), free liquid water in cell cavities above FSP, and water vapour. Water presence in wood cell walls and cell voids (over-hygroscopic range) is the fittest configuration for optimal fungal growth in lignocellulosic SSF. We can also note that fungal decay by oxidation produces water along with CO_2, but is not a phenomena that is considered for modelling in this context. Similarly, the freeing of bound water under the action of decay that influences the moisture content as substrate dry mass loss is occurring if the system is closed, is not modelled. Lastly, the effect of water activity upon turgidity and enzymatic activity is not modelled. The simulation model can be used with hypothesising these non-modelled experimental factors as fixed, and can be used to explore the remaining of the design space allowed with its parameters (input datasets and tuning parameters).

The simulation is based on a spatial discretisation in the form of a volumetric point-cloud representing the volume of a substrate. The moisture dynamics simulation model comprises two sets of phenomena: evaporation and capillarity. The effects of fungal decay over moisture release from the substrate by cell wall decomposition, and carbohydrates oxidation, are not modelled. Water activity is not present either, but can be considered at calibration stage. The model resolution aims at being set at the scale of 1 – 5 mm distance between points of the cloud, and although it represents fungal growth as a graph, it does not aim at modelling hyphae networks but regions and patterns of colonisation. The macro fungal growth that is simulated represents the mycelial exploration of a substrate. The model takes four datasets as input: an initial moisture distribution map, a thermal map, the position of fibres within the volume, and the position of mycelium seed points. At iteration n, evaporation is simulated such that the moisture contained at point p is being partially transferred to its neighbours within an influence radius, in an eccentric manner to the favour of the neighbouring points situated above p, and depending on the warmth level at p. Capillarity is simulated in a similar way, but instead of considering neighbouring points it refers to clusters of points within a fibre and distributes moisture from p situated within a fibre, depending on its warmth level, within an influence radius, and in any orientation of the fibre (gravity is neglected). From a set of seed points within the point cloud, mycelial colonisation is simulated as a graph that follows the iterations of the moisture dynamics with a minimum moisture level parameter allowed for the growth, and a maximum branching level.

The model as defined is subjected to uncertainty: evaporation and capillarity simulations are meant to be accurate enough to be calibrated and instrumentalised for design purposes, but depend on complex models that are only approximated here. For this reason, and to convey the conceptual framework mentioned in section 2.1, this model was made stochastic. Therefore, each data point in the three initial datasets (warmth map, moisture map, and fibres parsing) has a corresponding probability. The determination of these are made manually by the user and are related to confidence in each input of the experimental setup. For instance, a user can set a high temperature on the external boundary of the experimental setup with a maximum confidence level of 1.0 as they can measure the value easily, and then set a lower temperature level at the centre of the volume of the experiment with a low confidence level as they may not be able to measure this temperature. While the simulation is being solved, the probabilities are being solved too as the intersection of the events at each point of the model.

3.2 *Mycelium-Based Composites methods*

The substrates and scaffolds materials were recommended to be prepared at 40 % MC with mineralized water, and sterilised at 117 ºC for 30 min. The substrates were inoculated in a variety of manners by the students. They were advised to mix the wet substrates with 16 wt% *Ganoderma lucidum* spawn (M9726, Mycelia BVBA, Nevele, Belgium) and to incubate them in PP filtered bags for 7 days at 25 ºC in the dark when relevant. The fungal species was selected for its widest carbohydrate-active enzymes array (CAZymes) (Zhou et al. 2018; Chen et al. 2012) and its colonisation rate, thus allowing students to reach quick conclusions with a high cultivation success rate. Among the most used substrates during the workshop were European beech wood (*Fagus sylvatica*), common reed fibres (*Phragmites australis*), and rattan fibres (*Calamus manan*). Students used a variety of supplementary materials such as glass, copper, or hessian (Rigobello et al. 2021).

3.3 *Evaluation method*

To assess whether the pedagogical goals have been met in the workshop, we have formulated two pedagogical hypotheses. They read as follows: a) *the teaching environment enables the students to articulate experiments with simulation use to support critical thinking development on the role of simulation models in architectural design*, b) *the teaching environment supports the students appropriation of the MBC conceptual framework*. In order to evaluate the pedagogical set-up and its consequences on the learning process of the students, interviews were conducted with each group of students. They happened on September 29th 2020, a day before students project presentation. The survey questions read as follows:

- What is your background prior to taking part in the Computation in Architecture master program? Did you have any knowledge of working with living organisms before this workshop?
- What are you working on during this workshop?
- Why have you chosen to explore this?
- Can you describe the experiments and simulations you have done and are planning?
- How have you been working with the simulations on one hand and the physical experiments on the other? How do you link them?
- How are the tools you were given helping you investigate the architectural potential of mycelium?
- What about the sensing protocol? Beyond the measures, do you have other sources of information on what is going on with the mycelium?
- How did you use the five key notions shown at the beginning of the workshop?
- What have you learned about working with mycelium?
- Do you think you can or will use this knowledge on other occasions? What architectural possibilities do you envision?

Since the 1990s, a great number of studies on architectural learning stemming from the field of design studies have been accompanied by research aiming at identifying systematic design methods in order to establish teaching models (for a review, see Demirbas¸ and Demirkan 2003). While only some of the existing studies identify architectural knowledge directly as tacit knowledge (Kruchten et al. 2005; Uluoğlu 2000), a great number identify the tacit dimension of the knowledge mobilised in architectural design, although they do not refer to it in this term, preferring notions such as *intention*, *intuition*, *implicit reasoning* or *empiric method*. To the knowledge of the authors, none of these studies assessed the development of tacit knowledge in an architectural teaching environment, despite the fact that diverse models are employed in existing studies to assess various aspects of the mobilised knowledge and methods in architectural training. In order to understand the knowledge transfer at play in our workshop, we have selected the SECI conversions model, which enables the assessment of tacit knowledge transfer (Nonaka, Toyama, and Konno 2000). This model has been conceived from the Japanese notion of *Ba*, a word that translates as "place". *Ba* designates a place and time collectively shared, and includes the mental space that is shared when a group gets together. This shared mental area provides a space for knowledge to be exchanged and the conditions of this exchange — and conversion — are what the SECI model assesses. It allows for the identification of four modes of conversion: *socialisation*, enabling a tacit-tacit knowledge conversion, and referring to moments of observation and imitation; *externalisation*, enabling a tacit-explicit knowledge conversion, and referring to explicating knowledge in writing or drawing, for instance; *combination*, enabling an explicit-explicit knowledge conversion, and referring to the use of existing explicit formats in order to produce new explicit ones; and *internalisation*, enabling an explicit-tacit knowledge conversion, and referring to the acquisition of tacit knowledge through the manipulation of explicit formats. The SECI model, named after those four conversions modes, envisions these as successive and has therefore been criticised for being too linear. We thus use the model as an analytical tool, not using the conversion modes in a sequence but independently: these modes have been coexisting in the workshop context.

4 EVALUATION

4.1 *Interviews*

Among the most prominent ideas that were discussed, and because it was a focus across the two parts of the workshop, the establishment of an iterative process between experiential learning and simulation exploration was a leading interest. The discussions oscillated between students reporting on the successful integration of experimental learning into the simulation (as per growth rate tuning, environmental influence calibration, capillary action tuning, evaporation rate and reach), with group 3 having confidently discussed their success at calibrating the simulation model, and four out of seven groups having brought up supplementary experimental series being necessary to them for improving the predictability of the simulation outcomes. We read this as a necessary development of a critical thinking as per the role of the model as an instrument, and a relevant feedback as the students were both in their first introduction stage with mycelium craft, and expected to appreciate a non simplistic relationship to fungi. Five groups discussed the resort to simulation as a means to probe architectural design as grounded into a cultivation practice, and used the simulation to imagine constructive methodologies for load bearing structures. With use of solar radiation analysis within the design workflow, all groups have developed scenarios utilising solar warmth and its effect on evaporation to design either hand handleable modules that can be assembled after cultivation, or on-site cultivation principles. As the students developed their tacit understanding of the craft, they productively criticised the lab cultivation conditions that systematically use substrate sterilisation for instance. Four groups have specifically commented on the limits of the simulation model and the constructive unpredictability in an on-site cultivation scenario because it would involve accounting for microbial coexistence. Beyond scaling, four groups have reported making use of the simulation model as a way to probe complex designs based on elementary experiments they conducted. A group reported their interest for using it to build a finer understanding of the colonisation at play with a volume of substrate, beyond vision, while group 6 documented experiments specifically testing a moisture-based powder bed printing lookalike method. Group 2 also ventured down this path, by rotating a composite during its cultivation so as to change the face being exposed to the sun and successfully influenced the moisture spread. Other groups have been using the simulation not to assess more complex craft methods, but as a means to establish hypothesis and evaluate experimental setups that they would not have had the time to perform.

Across groups, the feedback regarding compressive performance appreciation was heterogeneous: two groups reported doubts as per the state-of-the-art mechanical performances of the composites, and two other groups expressed their surprise regarding the good stiffness of MBC. This perception reflects the architectural potential that the students envisioned. Some groups praised the more-than-human collaboration with a mycelium, mentioning resulting forms that we would not intuitively trust as humans, making it an opportunity to challenge pre-existing ideas of comfort, pleasure and sterility. The smell of MBC was flagged as intense by a group, opening a productive conversation that started from the need to cancel it and went on to refer to the comforting perfume of wood: ”Do we grow to enjoy the smell of wood, or do we instinctively appreciate it?”. For some, it was a potential unpredictability combined with the exploration that was motivating. A student interestingly reported that the craft - the process - was similar to doing a renovation project that necessitates the rediscovery of obsolete constructive methodologies and materials. While acknowledging that MBC can be controlled and be made stiff and resilient, notably with the introduction of glass and cotton in the substrate, some students advocated for the necessity of the craftsperson to also be sensitive to the colonisation and mycelial expression for allowing the full expression of the craft. Echoing the smell controversy, the same group went on with the idea of comfort to envision fungal architectures as uterus-like, where elements are swollen, soft, and reminding of embryo state.

Throughout the interviews we read a good appropriation of critical thinking on the role of simulation models. Overall, the introduction of the stochastic layer to the simulation model added a third level of learning to the workshop in addition to MBC craft introduction and getting introduced to computational design and its functioning. No explicit mention was made of this aspect in the interviews, and although each group made some sense of it in their submissions it is obvious that the combined complexity of the three key notions was detrimental to the students appropriation of the stochastic functioning. Its contribution is hardly distinguishable from other factors of the pedagogical environment, but the considerable involvement in crafting by experimenting creatively and the resulting conceptual appropriation beyond considering MBC as sole materials can surely be credited for a part to having made uncertainty a defining trait of the model.

4.2 *SECI conversions*

In order to discuss the insights obtained through resorting to the SECI model, we discuss the events of the workshop through the review of the knowledge carriers in presence as well as through the examination of the activities that took place. Both then serve as a basis to establish which conversions happened during the workshop and whether their presence or absence yielded the expected results. Written carriers include the teaching support document, and the presentations produced by the students as a final deliverable (Rigobello et al. 2021) Knowledge carriers also include the physical objects crafted by the students. We consider these objects to most prominently carry a different form of knowledge, as it is a trace of the craft somatic knowledge acquired by the student. In particular, the attention to materiality that they demonstrate through the combination of materials in the substrate and its colonisation by the mycelium acts as a trace of that acquisition. In that sense, while written knowledge carriers testify to the existence of externalisation and combination modes in the workshop, the objects testify to the existence of socialisation. Furthermore, the workshop as a learning space has been the opportunity for other occurrences of socialisation as well as of internalisation, both through the observation and imitation of model manipulation and of craft practices. The interviews confirm that these latter conversions, happening in the workshop space, have played their role in the acquisition of new knowledge by the students. The presence of the four SECI conversions and the confirmation through interviews and documentation of their impact on knowledge acquisition thus validates the pedagogical set-up by providing insights on how explicit and tacit knowledge have been transmitted. The workshop as a teaching format is a fit environment for architecture students to acquire a relevant knowledge set thanks to the modalities tackling both explicit and tacit knowledge acquisition. This is confirmed by assessing the materials produced by the students with regards to the two hypotheses we formulated previously. The sheer diversity of objects and experiments that students crafted are a testimony to this. So is the student's visual production, which mobilises the technical information provided in writing as well as exploring various modes of representation provided through the *P. stellaviatori* tutorials. The documentation produced by the students highlights their attention to material choices, shown carefully through composition detailing and texture focuses. It also highlights their appropriation of the various factors influencing mycelium colonisation which is reflected in the architectural proposals.

5 CONCLUSIONS

In this article, we have presented the conceptual framework for developing the *P. stellaviatori* simulation model as a pedagogical instrument. We have reported on the pedagogical theoretical framework we adopted for evaluating the effectiveness of the simulation model as part of the proposed teaching environment, and have presented a comprehensive analysis of student group interviews specifically informed by the SECI model. Craftspersonship was a central theme in the interviews, be it indirectly through reports on somatic perception (i.e. smell for instance), or directly in the constructive methodologies of student proposals and their instrumentalisation of experiments regarding the simulation. With the first half of the workshop having been focused on the MBC craft initiation, the craft nudge allowed by the simulation model is identifiable through the moisture focus that students developed in their tests. All groups have adopted this focus, and its integration with solar radiation analysis led part of the students to experiment outside of lab conditions to test context hypothesis. This had a productive influence over their architectural visions, and across the seven groups a diversity of grounded constructive methodologies are presented in the supplementary materials (Rigobello et al. 2021). Finally, while we acknowledge the density of the expected learning in this constrained workshop period, our learning hypotheses have been corroborated; they regarded the development of a critical thinking as per the role of simulation models in design activities, and the acquisition of a somatic tacit knowledge for a MBC conceptual framework. This leads us to conclude on the effectiveness of the use of this simulation model as a pedagogical support embedding traits that facilitate the setting of an applied and conceptually situated knowledge, that is within the larger set of used teaching media.

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