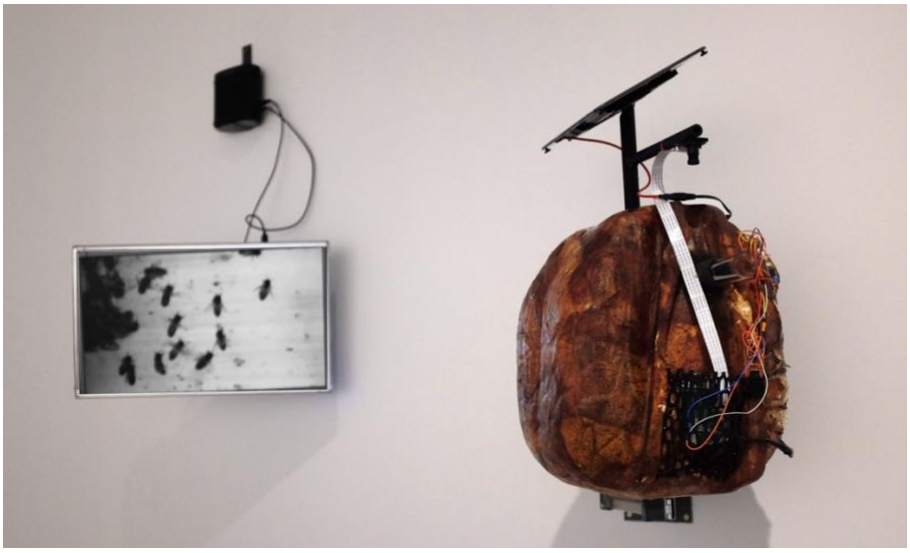
The Intelligent Beehive and the Genesis of a Microbial Skin.



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Abstract

For most of the past decade I have been growing, hacking, digitizing, building, and thinking about beehives - particularly those in urban areas. Collaborating with a team of biologists, I am reconceptualizing what a beehive is and what it can be. The bio-art project The Intelligent Beehive monitors the behaviour of urban honeybee colonies as a source of inspiration for ongoing artistic research into issues of ecological, architectural and social sustainability in urban environments. Bees are bio-indicators. They reflect the health of their surrounding ecosystem as well as the cumulative effects of different pollutants. In many industrialized regions the colonies are threatened. Air pollution, the compromised state of their foraging fields, pesticides and parasites are among the main factors. To raise awareness about the disappearance of the honeybees, I imagined the concept of an Intelligent Beehive. It is a radically new beehive. Tailored to the needs of the bees (instead of those of the beekeeper), and augmented with supportive bacteria, it is intended to help the bees in their survival and pollinating tasks, and thus protect the biodiversity of the environment. My Intelligent Beehive has been a starting point for exploring possible futures through artistic research on materials science and biotechnology.

The Intelligent Beehive Project

For a large part of the past decade, I have been growing, hacking, digitizing, building, and thinking about beehives – particularly those in urban areas. Collaborating with biologists, designers and engineers, I have been re-conceptualizing what a beehive is and what it can be. This has led to the speculative bio-art project 'The Intelligent Beehive'. The project imagines a new kind of beehive which is both a safe, healthy haven for swarming urban honeybee colonies as well as a device for monitoring their behavior. This long-term project has been an incredible source of inspiration for artistic research into issues of ecology, architecture and social sustainability of urban environments.

My research navigates between experimental urban horticulture, scientific research, and metabolic sculptures. My experiments connect living, intelligent systems and biotechnology with artistic and technological prototyping and experimentation. The toolset includes microbial life and material science in an attempt to develop bio-remedial beehives. It also includes various measurement and information technologies such as scanning electron microscopes (SEM), sensors, Big Data cloud storage, signal processing, and Artificial Intelligence. The artworks that result follow a complex work-methodology combining firsthand observation in research gardens and rooftop apiaries, laboratory probes, and digital monitoring. [1]

My work not only gives rise to fascinating images, useful ecological data and new ideas for building sustainable beehives. It is also a political statement, arguing for the integration of nature as a social/sensory/phenomenal living matrix. This matrix takes shape in collaboration with bees and their urban foraging. The resulting theory and practice emphasizes fairness to nature. Specifically, it draws attention to the fragile affinities between humans, bees, bacteria, and the urban neighborhoods they symbiotically inhabit.

The images in this paper will illustrate both the laboratory setting and some of the art works that have come out of the Intelligent Beehive project.

[1] *Maes, A (2013). The Transparent Beehive Notebook. Brussels: OKNO – Art / Ecology / Technology*

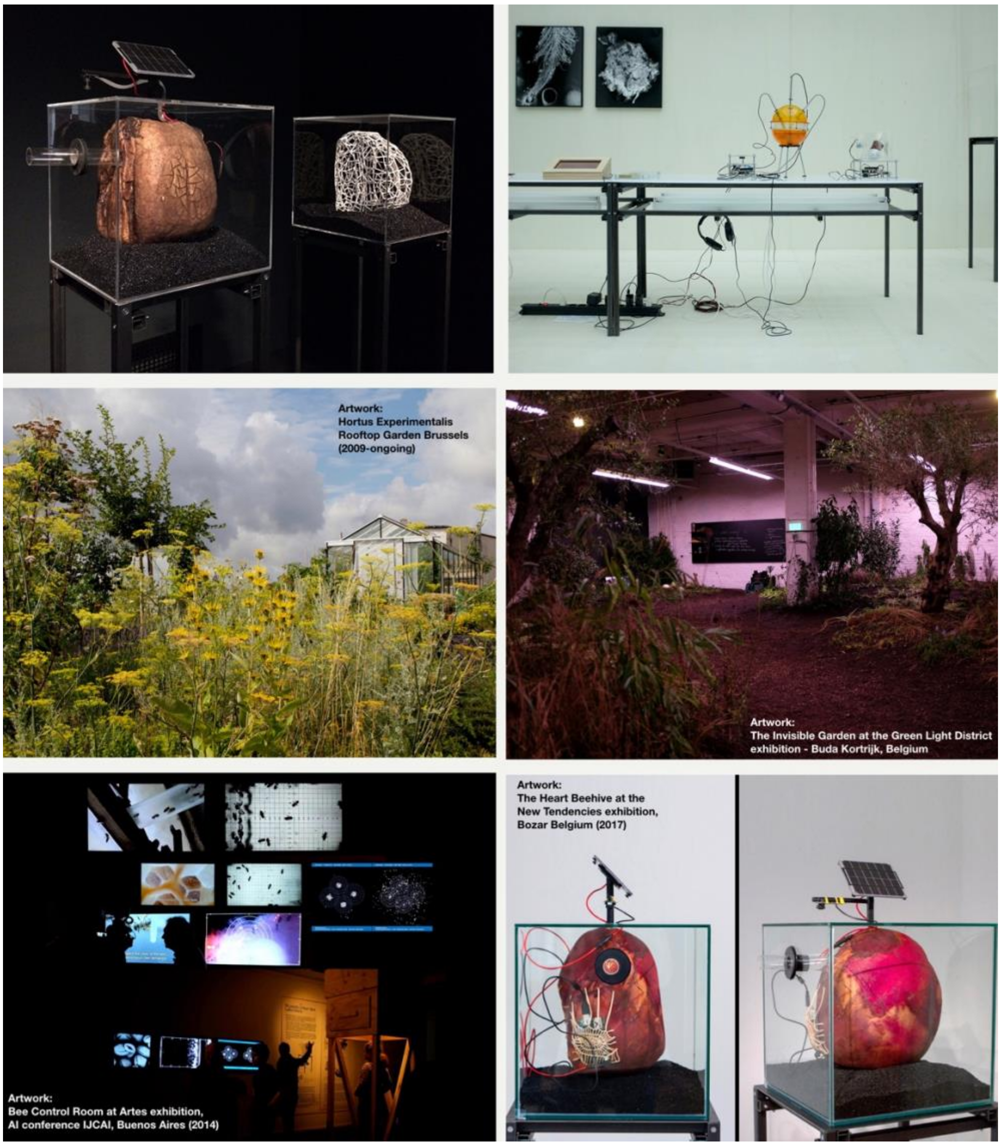

Figure 1. *Artworks resulting from the Intelligent Beehive research - © AnneMarie Maes*
From left to right, clockwise: the Intelligent Beehive at Ars Electronica, 2017; the Intelligent Beehive at Ispra/Milano, Museum of Technology Leonardo Da Vinci (2017); The Invisible Garden at the Green Light District, Kortrijk, Belgium (2014); the Heart Beehive at Bozar, Brussels (2017); the Scaffolded SoundBeehive at Centro Luis Borges, Buenos Aires (2015); Hortus Experimentalis at SO-ON, Brussels (ongoing).

Most of the fieldwork is carried out in the Brussels Bee Laboratory, an open-air lab which includes a 750 m2 rooftop garden directly connected to my studio in the center of Brussels. The lab contains a section where I grow plants for my biological experiments, as well as a set of custom-made observation beehives that are augmented with monitoring technology and that are streaming huge datasets on bee behavior to local servers. Bees are important bio-indicators. They reflect the health of their surrounding ecosystem as well as the cumulative effects of different pollutants. Given the decline of the bee colonies worldwide, it is important to map air pollution, the compromised state of their foraging fields and the presence of pesticides and parasites.

In cooperation with researchers from the Artificial Intelligence Lab of the Free University of Brussels (VUB) we started analysing this data using sophisticated pattern recognition, AI technologies, and we have used computer graphics for making these patterns accessible. The project has included an experiment in Deep Learning to interpret the activities in the hive based on sound and microclimate recording.[2] The conclusions of these observations formed the basis for the development of the Intelligent Beehive, a project which will make the transition from green technology to biotechnology and grow a radically new beehive from scratch - a beehive that is tailored to the needs of the bees instead to those of the beekeeper. Adding symbiotic bacteria to the skin of the hive might create a favorable ecology to support the bee colonies in their survival and hence reinforce pollinating tasks and protect the biodiversity of the environment.

[2] *Maes, A (2015). The Scaffolded Sound Beehive. Proceedings of the Twenty-Fourth International Joint Conference on Artificial Intelligence (IJCAI 2015)*

Figure 2. *Clockwise, from left to right: The Laboratorium for Form and Matter, Brussels; Researcher/Beekeeper at work; streaming computer; Intelligent Beehive prototyping; bee colony observation and analysis.*

The Intelligent Beehive serves as a physical model for biological actions in conjunction with technological fabrication (3D printing, laser cutting, CNC milling). It is appropriate to envision a metabolic sculpture, a ‘living machine’ expanded by green technology (a solar panel, camera, Raspberry Pi computer) and by living technology: bacteria. This vision incorporates bacteria as contributing agents, enabling the Intelligent

Beehive to autonomously interact with the bees, mites and urban environment. The intelligent device, combining nature and technology, calls into question not only machine-to-insect intelligence, but also questions how we deal with biological performance in hybrid materials.[3] The cellulose skin enveloping the beehive is augmented with a biofilm populated with colonies of bacteria. Their changing colors reflect the degree of environmental contamination. At the same time the device monitors the bees' microbiome. The prototype is placed into a sealed container to feed the bacterial colonies in a continuous way. The bees leave the hive via a tube.[4]

My motto for the design of the Intelligent Beehive was: grow a resilient structure and take nature as a parameter for form. Palynology (the study of pollen grains) offered a good starting point for the first blueprint drawings of the in-and outside. Pollen contains useful information on the environment, for a wide range of purposes but, moreover, pollen are of an extreme aesthetic beauty and their functioning is full of interesting little tricks (e.g. ventilation/stomata, thermoregulation, reflective and absorbing textures, apertures, resilience) for survival. They turned out to be an incredible source of inspiration. To translate these natural qualities towards a prototype created with digital technologies I needed to make an in-depth study of pollen. I started to work with the Scanning Electron Microscope (SEM) at the Free University of Brussels (VUB). The SEM offers the possibility to visualize small 3D objects (particles) up to +20,000 magnification, ideal for studying and photographing small particles as pollen grains, and pollution particles, which are daily transported within the electrostatic fur on the bees' bodies. Working with the SEM gave me

[3] *Maes, A (2017).* The Sound Beehive Experiment*. Acoustic Space Vol.16 / Renewable Futures, Issue 1.*

[4] *Maes, A (2017). The Intelligent Guerilla Beehive. Ispra/Milano: JRC Resonances.*

also a much better insight into the functioning and morphology of a bee, an important fact whilst developing a radical new hive that is bee-centred. When the bee lands upon the outer skin of the beehive, these pollution particles come in contact with the bacteria living in the upper biofilm layer which is enveloping the outer shell of the Intelligent Beehive.

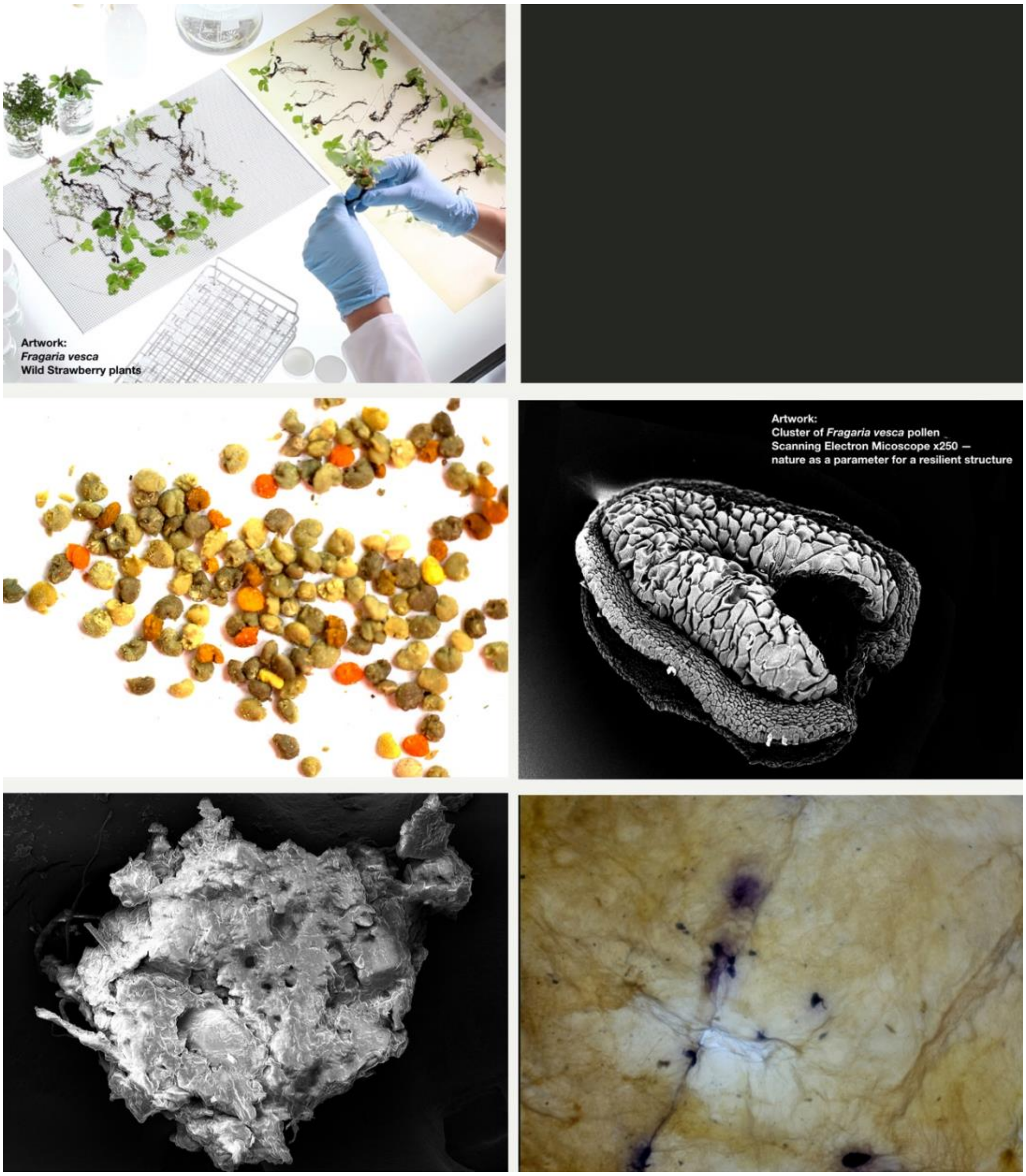

Figure 3. *From left to right, clockwise: Fragaria vesca (wild strawberry) as source of inspiration; Scanning Electron Micrograph of Fragaria vesca; biofilm with Janthinobacterium Lividum on cellulose fabric; Scanning Electron Micrograph of pollution particle (x250); pollen collection.*

Genesis of a microbial skin.

The research and development of the Beehive has been a constant exploration on the edge of art, science and biohacking. The goal is to provide a biological skin for a beehive, a skin that functions as an interface to compute and communicate the outer environmental data and the internal beehive signals.

I started to work with 'bacterial skins' as programmable material. A 'bacterial skin' (or cellulose skin) is a mat-like cellulose structure built of nanofibers. It is grown in a symbiotic action by bacteria and yeast cells. The Acetobacter xylinum bacteria produces a lot of cellulose; they are fed with a by-product of the yeast fermentation. Vice versa, the by-product of the bacteria fermentation feeds the yeast cells. The cellulose mat protects the fermenting sweet tea – the growth medium - from invasion by wild bacteria and yeast cells. The low pH of the culture disrupts the cell membranes of unwanted bacteria. Moreover, several of the healthy organic acids that create the low pH demonstrate specific antibacterial, antiviral and other antimicrobial properties. This is one of the main reasons why I choose to work with bacterial skins as a primary medium for growing the Intelligent Beehive.

I experimented with different technologies to create the skin: on a 3D printed skeleton (in chitosan), bacteria grow and from scratch they create a cellulose fabric which is later augmented with a supplementary biofilm with pollution-sensing bacteria. As such, the beehive becomes a sensing device. The double-layered skin of the Intelligent Beehive behaves as a bio-digital living system, the living matter itself (the bacteria) becomes the monitoring technology. In parallel experiments we investigate the possibilities of adding chitine/chitosan on top of the microbial skins, to enhance the skins' qualities of resistance, waterproofness and strength.

During the course of my research, I have combined organic components such as vegetal matter, pollen and chitin with living systems such as bacteria and other micro-organisms. Biomimesis (the imitation of natural models for the purpose of solving human problems) has been used as a starting point for incubating ecological thinking on matter and form. I have experimented with micro-organisms and organic materials to create thin membranes grown by a symbiotic community of bacteria and yeast cells. Following this, I have researched how these fabrics could be enhanced through embedded electronics and living technology.[5] The main question was whether the microbial-grown skins would be a valuable host medium for biofilms filled with a different strain of microbes, useful for environmental sensing. If so, then the multiplexed membrane could become a real smart fabric with integrated elements for sensing and actuating, for computation and for communication. The double-layered skin of the Intelligent Beehive behaves as a bio-digital living system, the living matter (the bacteria) becomes the monitoring technology. Different qualities of microbial skin have been examined in terms of strength, water resistance and aspects of the host as growth medium for the bacteria. In parallel, experiments were investigating the possibilities of adding chitin/chitosan on top of the microbial skins.

The Lab experiments were carried out between 2015 and 2017 in the Brussels Laboratory for Form and Matter; in the Biohacklab Barcelona and at the University Pompeu

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[5] *Maes, A (2015). Intelligent Guerilla Beehive - research page, https://research.annemariemaes.net/doku.php?id=guerillabeehive-researchpage*

Fabra in Barcelona; as well as at the laboratory of Chemical Engineering of the Free University in Brussels. I grew hundreds of microbial skins in plastic containers of different sizes and in a range of different environmental conditions. It turned out to be evident that the warmer the temperature the faster the bacteria were layering their cellulose nanofibers that form the matrix of the skin. But also, the quality (freshness) of the mother (the scoby), the quality of the tea leaves in the growth medium (green, black or perfumed) and the airborne spores of yeast specific to the location in which the containers are stored for growth (conflictingly or harmonious) are important parameters for growing a healthy and strong membrane.[6]

Figure 4. *From left to right clockwise: cleaning and testing wet cellulose skin; petri dishes with bacteria, samples and tests; inoculating cellulose skin with Janthinobacterium lividum.*

[6] *Crum,H & LaGory, A (2016). The big book of Kombucha. North Adams (MA): Storey Publishing.*

To enhance the water resistance of the cellulose skin, I carried out a series of tests with different compositions of chitosan on top of the wet and dry samples of cellulose skin. Initially, the idea was to 3D print a complete chitin skeleton for the Intelligent Beehive. The tests with different combinations of chitosan (mixed with different percentages of glycerol; with bacterial cellulose pulp or with crystal cellulose) have proven that working with chitosan is very complicated. The matter must be heated up to 75°C and needs to be stirred for at least 5 hours continuously. 2D drawings that have been created with 9% and 12% chitosan mixtures, with a syringe as a simulation tool for a 3D print head, turned out to produce satisfactory results initially – but the outcome is still miles away from the strong material that we need to make solid 3D skeleton prints. Much more research (and much more money) is needed to raise this process up to the scale of a workable material. Instead, I have set up an experiment for growing bacterial cellulose immediately around a 3D object.[7] A 3D-printed model of the Intelligent Beehive, slowly rotating in growth medium, gathered a 4mm microbial skin over the course of 4 weeks.

The last phase in the project was the search into finding the right strain of bacteria to populate the biofilm. Requirements are i) resilience in diverse environmental conditions and ii) color changing qualities when a specific ecological threshold is passed. To start this experiment, I left some wet cellulose skins in a beehive for a few days on which I was hoping to collect interesting bacteria in a natural way. I made several swabs of these skins, and these results were put to growth in a sterile container with medium. In a second phase I

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[7] *Maes, A (2015-2017). Grow your own Beehive, https://research.annemariemaes.net/doku.php?id=grow_your_own_beehive*

brought strikes of this medium to culture in petri dishes. Several strains of bacteria have been recovered from those samples but most of them were not useful for the experiment. After a series of attempts to make the bacteria grow on the cellulose skin, I have concluded that only the Lactobacillus plantarum and the Janthinobacterium lividum (2 strains that were bought) were able to survive on the skin. Bacteria from these 2 strains do not only grow into a biofilm, they also change color when a modifier threshold (pollution, pesticides) is passed. Following these results, I inoculated freshly grown skins with Lactobacillus plantarum bacteria and with the presence of X-gal (a modifier which is used in molecular biology to test for the presence of a specific enzyme) the bacterial colonies changed into a greenish-blue color, which is clearly visible on the skin of the little beehive model. As long as they are fed, the bacteria in the biofilm continuously renew into young generations, hence the cellulose skin acts as a crust that crumbles under ever new layers of bacteria. Thus, the Intelligent Beehive's outer skin is protected by a layer of living cells that constantly feed off the dead ones and thus cleans and repairs itself.[8]

[8] *Maes, A (2016-2018). Dyeing with bacteria. https://research.annemariemaes.net/doku.php?id=dyeing_with_bacteria*

Figure 5. *Clockwise from left to right: growing cellulose skin on a rotating object; bacteria hunting in the forest, Lactobacillus plantarum on dry cellulose skin; Lactobacillus plantarum on cellulose skin grown around an object and a 3D printed scaffold/skeleton of the Intelligent Beehive.*

Conclusion

The Intelligent Beehive hypothesis is a proof of concept. Experiments conducted in the laboratory as well as in the field confirm that the physiognomy of the beehive-object meets the conditions that a colony of honeybees needs to survive in the wild.

The cellulose skin, which envelops the beehive and which is built in symbiosis by *Acetobacter xylinum* bacteria and yeast cells, proves biotechnologically to be a good scaffold for growing biofilms of *Lactobacillus plantarum* or *Janthinobacterium lividum* bacteria. These bacterial biofilms react to environmental pollution thresholds by changing their color. As such, the outer skin of the beehive becomes a biosensor; it becomes an interface that visualizes the health status of the environment.

A negative point is that neither *L.plantarum* nor *J.lividum* are resilient to extreme heat or humid weather conditions. These bacteria only grow in a protected environment, and they need a steady flow of growth medium. A further search for the right bacteria strain is thus needed. Probably this problem can be solved with the implementation of synthetic biology. More research needs to be done into i) the water resistance of the cellulose membrane, as well for ii) 3D printing scaffolds with chitine/chitosan. We need support from a professional laboratory with the right high-end equipment to bring this experiment to a good ending.

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References

Maes, AnneMarie. *The Transparent Beehive Notebook*. Brussels: OKNO – Art / Ecology / Technology, 2013.

Maes, AnneMarie. *The Scaffolded Sound Beehive*. Buenos Aires: Proceedings of the Twenty-Fourth International Joint Conference on Artificial Intelligence – IJCAI, 2015.

Maes, AnneMarie. *Intelligent Guerilla Beehive - research page*, 2015 – 2017. https://research.annemariemaes.net/doku.php?id=guerillabeehive-researchpage

Maes, AnneMarie. *The Sound Beehive Experiment*. Acoustic Space Vol.16 / Renewable Futures, Issue 1, 2017.

Maes, AnneMarie. *The Intelligent Guerilla Beehive*. Ispra/Milano: JRC Resonances, 2017.

Crum, Hannah and LaGory, Alex. *The big book of Kombucha*. North Adams (MA): Storey Publishing, 2016.

Maes, AnneMarie. *Grow your own Beehive*, 2015-2017. https://research.annemariemaes.net/doku.php?id=grow_your_own_beehive

Maes, AnneMarie. *Dyeing with bacteria*, 2016-2018. https://research.annemariemaes.net/doku.php?id=dyeing_with_bacteria