Intelligent Beehives as Predicates for Metabolic Architectures

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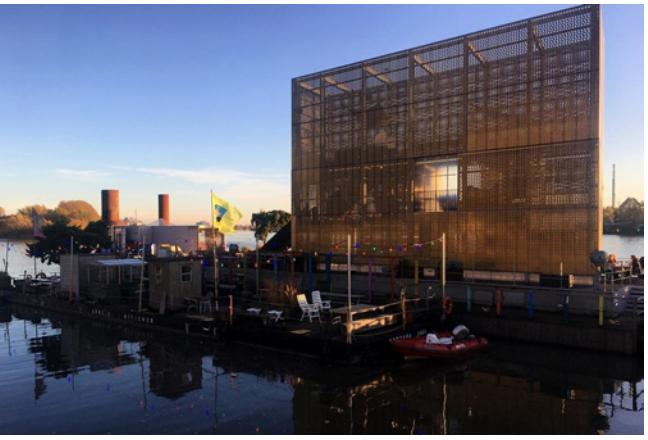

Figure 1.
The Entenwerder Golden Pavilion on the Elbe River. Hambourg. The site for AnneMarie Maes's installation, ElbBienen (Elbe Bees).

Keywords
Intelligent Beehives. Art. Urban Bees. AI. Bacteria. Hambourg. Urban Design. Public Art. Metabolic Architecture. Urban Sculpture. Installations. Environment. BioFilms. Nature-Surveillance. Computational Fabrication. Living Technology. Bioremediation.

Theory-driven architecture may be organized to encode and set procedures for research-by-design seeking data from prototyping as an extension of art. Through art, a research scaffold may emerge for exploratory architectural experimentation and discussion. Associatively, interlinked sets of observational data, sensor readings, laboratory tests, environmental analysis, and fablab models permit potential hybrid materials to embed data for exchange between science, design, and urban sites. Enabled data and observations herein act as foundations for reasoning a building or sculpture's inclusion of AI, synthetic life, and bio-algorithmic performance as part of evolutionary nature.

Critically, in relation to AnneMarie Maes's research, it is human-to-bee intelligence and evolutionary nature I looked to for underpinning metabolic architectures and urban infrastructures as they call for new typologies of environmental bioremediation. I emphasize Maes's artistic practice developed over the past ten years focused on her urban beehives as first instances of metabolic buildings. These art and nature works demonstrate applications of bee and microbe architecture mediated by technology, biology, and artistic insight reported here in the urban context of architectural intelligence. In this milieu Maes's *ElbBienen* (Elbe Bees) exhibition, presented as part of the *Hamburg Maschine* (Hamburg Machine) at the city's Entenwerder Golden Pavilion (Fig. 1), is scrutinized for artistic vision capable of dialectically tutoring metabolic architectures in biological intelligence and AI environmental/cultural crosstalk.

In relative terms Maes's intelligent hives — bee-buildings — teach us about advanced approaches for architectural machines. Mae's beehives push biological-natural interactions in directions of enhanced ecological performance we normally register only in extreme artificial environments such as AI-regulated space stations, arctic research outposts, submarines,

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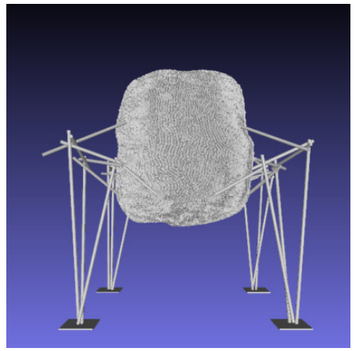
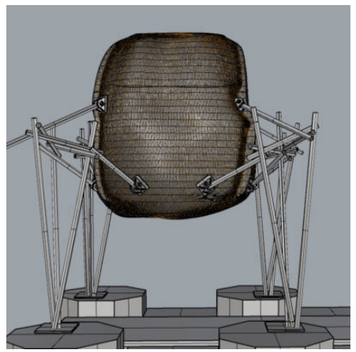




Figures X. & X.
Digital renderings for visualizaing the hive before fabrication.

or even airplanes — all whose interiors are continually monitored and adjusted by sensors and computation. Those shell or monocoque constructions interface the environment as membrane/panels. In this consideration, the beehives Maes builds are metabolic thin-walled constructions similarly interfacing bioactive urban nature. Her designs have biodigital and cellularly intelligent responsiveness in realms that prompt questions never before posited in relation to buildings and cities.

For instance, if a metabolically intelligent building could experience nature in ways similar to her beehives (involving microbes, plants, animals, and/or AI), could it be evolved as biodigitally sentient? And: Would advanced metabolic buildings exist in realms of artificial life approaching consciousness?[1.2.3.4] Here, for a anatomical analogy, consider the machine-fabricated thin biological walls of *ElbBienen* as beehive equivalents of bioactive building curtain walls, panels, or skins. They function as architectural prototypes for influencing bee-to-human learning illustrating how artworks significantly push boundaries to evolve urban and building design.

Aptly, Maes milled the Hamburg beehive (and its sister in Brussels) with a CNC programmed Kuka robot (Fig. X. X.) in collaboration with the digital woodshop at the University of Applied Arts, Vienna. The Kuka's tool path (Fig. X) was intentionally instructed to cut waving patterns enveloping the hive's exterior thereby enabling wild microbes, moss, and/or lichens to colonize the hive's surfaces. The hives are thus hybrids of robotics, biology, and artistic intention. Their physicality reflecting a digital heritage steeped in machine intelligence and tooling expressed in their wavy, exoskeletal walls. Those walls are further made active between resident bees and monitoring technology (cameras, sensors, and programming) embedded by the artist.

By formulating questions of hybridity, not frequently asked, yet lurking behind, for instance Google's AlphaGo,[5] AlphaZero,[6] and AlphaFold[7] — ontological nature-to-machine communication enters realms of design dialogue involving AI, synthetic biology, and evolution. Nevertheless, further questions are pertinent for considering Google's DeepMind implementations of neural-net AI-learning, playing, and winning

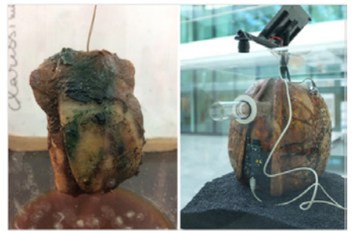


Figure X.
The Intelligent Beehive, 2016-2017. Two views of the 3D printed beehive, clad with microbial cellulose skin and inoculated with Lactobacillus plantarum bacteria growing into a biofilm. © AnneMarie Maes.

Figure X.
Kuka robot and part of the Intelligent Guerrilla Beehive during fablab building in collaboration with the University of Applied Arts, Vienna.

Atari video games, beating world champions at the Game of Go, triumphing over human and machine chess players, and aiding doctors in medical diagnostics. If, as widely reported, programmers cannot fully understand how some of those feats were processed,[10. 11] should we anticipate a neural-net category of AI/biological species that is existentially, phenomenally, and/or experientially capable of learning, teaching themselves, and autonomously interacting with us and the environment.

Those unexplained realms of machine intelligence foreshadow the first appearances of artificial consciousness and sensibility[1. 2] through which *Science Magazine* defined a debate: "What would constitute successful demonstration of artificial consciousness?"[1] To this question of sensibility, consciousness, and cognition, Maturana and Varela established a theoretical foundation in *Autopoiesis and Cognition*[12] from which I evolve underpinnings for justifying metabolic architectures based in biological theory. They wrote:

> [L]iving systems are machines, that they are physical autopoietic machines is trivially obvious: they transform matter into themselves in a manner such that the product of their operation is their own organization. However, we deem the converse is also true: a physical system [metabolic architectures or Intelligent Beehives], if autopoietic, is living.[12]

After all, learning, distributing, and acting upon knowledge is something people have considered core abilities, preeminently human. In reality however, microbes, plants, and the vast range of planetary life participate in differing types of metabolic intelligence not predicated on human models. These new beehives occupy a niche in that category where research tactilely and intellectually acknowledges vast discrepancies in realms of metabolic intelligence displaying physical morphologies such as shells, nests, boroughs, hives, and (human) houses. *The Hamburg Machine* exhibition thus emphasizes another zone of occupation leading to different questions: Under what conditions do we recognize a beehive (or a machine or building) as metabolic and/or intelligent? I shall extrapolate from

such queries using Maes's experimental hives for application to building and cities along lines I use to teach her works to master students in biodigital and metabolic architectures.[25]

The above may seem disjointed, distant from how we think of future cities, buildings, and the technologies. But Maes's research is a pathway for us to imprint and understand experimental realms of art as prototypes for architecture and urban design in concert with living organisms — not only with bees — but also with microbes and plants (and AI).[13] Understood as relevant to urban nature and culture, Maes expresses mechanisms for sustaining urban species, community gardens, parks, and waterways while her multifaceted research parallels architectural and urban requirements.

Specifically, in this case, Hamburg is supporting it's city curator (stadtkuratorin) Dirck Möllmann's exhibition *Hamburg Maschine* in a search for new visions and dialectics for urban art as a response to scientific and technological breakthroughs and their huge impact on city life, aesthetics, and environment. In the framework of urban space and habitation, I consider Maes's bees as resident citizens — indicators of urban biodiversity. Neighborhood bees are biologically intelligent engines of pollination — biomonitors of urban toxins — thus engines not only of planetary life, but also neighborhood well being made apparent by apiary friendliness.

The Intelligent Beehive lineage spans Maes work through incarnations begun with The Transparent Beehive (2012) followed by the first biologically performative Intelligent Guerrilla Beehive (Fig X). In that metabolically active work, bacterial (biofilm) functionality appeared in her research involving bacteria, algae, and lichens. In this framework, the Hamburg/Brussels hives are the first to be occupied by bees and field-tested in public realms and live-streamed.[14] With bacterial experiments ongoing in collaboration with the Open Biolab in Brussels (and forthcoming with Vrije University in Amsterdam), it is expected that future hive physiology will unite with cyanobacteria functionality for an organic energy source serving the digital systems within the bee colony as predicted in the first Intelligent Guerrilla Beehive (Fig. 2). (Research into bacterial agents as participants in hive materialization and metabolic

Figures X. & X.
Top: Kuka robot and part of the Intelligent Guerrilla Beehive during fablab building in collaboration with the University of Applied Arts, Vienna.
Bottom: Kuka milled beehive test assembly, Brussels. April 2019.

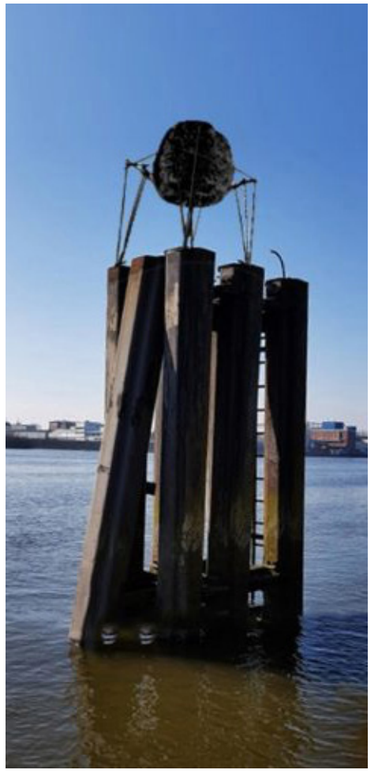


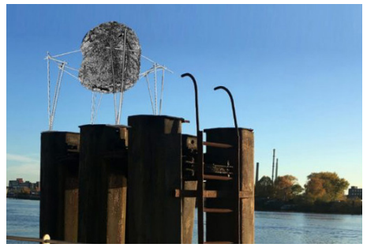
Figure X.
Artist's collage of the Intelligent Guerrilla Beehive on Elbe River piers in front of the Entenwerder Golden Pavilion, Hamburg.

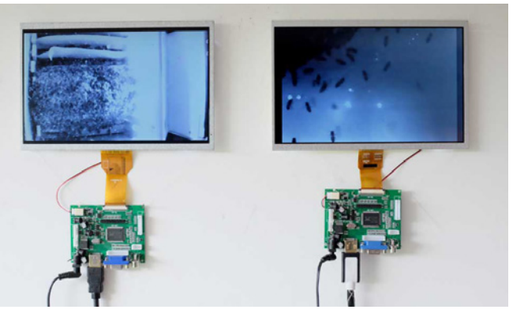
architectures is discussed in a collaborative article by Dollens/Maes due from *Leonardo*[15] in 2020).

Considering the Hamburg/Brussels hives, I'm not suggesting one-to-one animal-like or plantlike parity involving microbial life/cognition with human intelligence. I am suggesting new domains of collaborative pairings between nature, computation, AI, and architecture where intelligent/biological abilities are searched for metabolically performative architectures. The Hamburg beehive and it's near relative in Brussels, become a case study for architecture and urban planning. The two hives suggest that subsequent buildings could be bio-fabricated hybrid machinic/biological organisms far beyond today's conceptions of prefabricated buildings for extreme conditions with robotic AI sensors and actuators.

In this unlikely combination — technological hives and urban bioAI buildings — we find new implications for buildings and cities that must be contemplated if biologically active architectures and bioAI computation become hybrid candidates for membership in intelligent nature. The claim for metabolic architectures as participants in nature stems from biochemical and biointelligent agents embedded in buildings to autonomously clean and monitor the environment. Furthermore, the implication of biointelligent architectures reorients malicious corporate surveillance and suggests repositioning their technology as sentinels, guardians, and instruments for bioremediation and toxic cleanup. This is contentious, if autonomous living microorganisms are considered for hybridization with machine intelligence, but taken out of a bioremedial environmental context — that's scary. Scary, because neural-net-AI, as noted above, has abilities to teach itself and modify its behavior based on its own research — it thereby crosses into areas humans allocate as domains of nature's intelligent life.

Using a pathway for an emergent theoretical entry, we may perceive the Intelligent Beehives as evolutionary in nature following Richard Dawkin's[16] theory of extended phenotypes and J. Scott Turner's *The Extended Organism: The Physiology of Animal-Built Structures*.[17] Through the argument of extended phenotypes, nature consist of objects and environmental interventions (earth works) built or produced by organisms





Figures X. X.
Streaming from Intelligent Guerrilla Beehives in Hamburg and Burssels for research comparison of hive and bee behaviors.

(microbes, plants, animals — including humans). Those interventions are dependent on genotype/phenotype impulses or responses to instigate (among other functions) the building of shelters that determine/influence the production of animal architectures and environmental works such as hives, nests, termite mounds, and skyscrapers.[16, 17] Consequently, we can place Maes's artistic vision and sensibilities as influencing urban and architectural crosstalk with genetic nature where human shelters, architectures, cities, and infrastructures retrieve "for human beings some lost dimension of their own animality, their own immersion in a world outside of language.[18]"

Extended phenotypes are thus biologically and urbanistically relevant. They emphasize biological perspectives through which humans maintain connections to primal animality while extending human connectivity to technological, computational, and scientific networks for tactical investigations of matter, force, and phenomena vis-à-vis nature itself.

Expanding boundaries of our animate, if phenomenal intelligences, like the expanding universe itself, is spatially and culturally situational and sometimes difficult to comprehend. Investigations, as constituted in this text, foresee building performance imagined/visualized through symbolic language, drawings, and design modeled on philosophical propositions philosophically anchored in Wittgenstein's *Tractatus*[19, 20] and the Vienna house he designed for testing *Tractatus* precepts in space, form, and Modernist design language.[21]

Investigations through language, computation, and design symbols incorporate and mold the artist/architect/designer's vision mediated by biological materialization, design, and spatial partitioning. Those investigations unify aspects of performative biocommunication whereby nature situates metabolic buildings/cities as potential species of hybrid biointelligence given form by integrating living technology[13] in a manner Maes's beehives pioneer.

This may sound over exaggerated, but benign or collaborative observation (bio-surveillance) in nature may eventually include communication between insects, microbes, forests, and humans. Mae's vision of built shelters suggest infrastructural ways by which humans can learn *Tractatus*-

Figure X.
Stereolighograph (STL) skeleton of an Intelligent Guerrilla Beehive with Scanning Electron Micrograph (SEM) of Glossa (bee tongue).

like mechanisms (operating systems) for participating in the conversation of nature — and, her own books furthers this continuum from *The Transparent Beehive Notebook*[22] and *Alchimia Nova*.[23]

Comprehending that bees communicate through a language of dancing, underpins their intelligence in relation to hive-to-design and discussions of urban/technological environments as sanctuaries when pesticides have made countryside living deadly for them. Furthermore, in the realm of language I speculate Wittgenstein would have acknowledged bee dancing as a kind of semaphore language. And, because bee language involves signing in bodily poses, positions, and alignments (the vocabulary), it is akin to his discussions of picturing (pictographs/glyphs) in the *Tractatus*. Bee movements cognitively transmit semiotic signals coding flight/landscape directions and plant descriptions in data cognized and transmitted in linguistic-like performances through bodily configurations linked by choreographed movement (the grammar). With infrared cameras as part of the hives suite of electronics and biological functions, observation and study become part of an Intelligent Hive's environmental performance.

The cultural and experiential propositions ingrained in Maes's *ElbBienen* for the *Hamburg Machine*, expand human-thought territories to include bee intelligence and their environmental protagonists and allies in an individual artist's visionary implementation of design-by-research. Resulting design/art implications embed, encode, and invite bioremedial formulations of matter, space, phenomena, language, AI, and intelligences. These may be debated as environmental assets directed to remediate environmental toxicity dating back to the industrial revolution. Furthermore, the environmental assets inherent or suggested in Maes's physical biomachines (the hives) may be collaborative with other scientific monitoring. For example, the use of honey itself, as reconfirmed in *Nature,*[24] reacts to urban pollution by registering trace Pb (lead) isotopic compositions and thereby hives/honey act as neighborhood geochemical biomonitors.

In this context Intelligent Beehives are hybrid biological, intelligent machines — urban sentinels, and pedagogical

markers the *Hamburg Machine* is hosting in order to introduce them to public scrutiny. Biological lab research and CAD/CAM fabrication then anchors artistic and architectural conceptualization intended to seed environmental relevance for ways of designing and restoring urban cores through the practice of art and design. As the cornerstone for an operating/research system — an OS verging on an ecological, bioremedial tactics, an ecological mind-set waits to emerge from *ElbBienen*. Such mind-sets will nurture differently oriented conceptions of nature, cities, technology, and individual intelligence opening new realms for thinking, projecting, and living with technology in wilderness and cities.

This is architectural and urban ecology at the level of interfacing species with living architecture. It promotes reconstructing and redesigning objects, tools, urban infrastructures, and buildings in conceptual frameworks based upon cellular intelligences as well as neural-net AI and ALife. The theoretical scaffold must therefore accommodate hybridizing materials with evolutionary procedures found only in science, technology, and design to reconnect nature's multitudinous cellular life/intelligences with current human lifestyles. Resulting organism/intelligences, compatible with synthetic life, AI, and neural-net learning are thus linkages for new types of performative machines, cities, and architectures.

From such linkages, I build this text for assembling bioactive agency and/or hybridizing it with materials following Maes's lead. Beehives fit into this profile and experimental mode. With remediating abilities, living technology and biological intelligences (including the designer's cognitive imprint), emerge as metabolic factors ready to be investigated, discussed, and applied to building design. Instances of this procedure require recognizing types of intelligence, potentials of AI learning, and capacities of generative computation perceived by the artist/architect as enacted in continuum with nature.

The act of defining intelligence is aided by theoretical autopoiesis[12, 13] situating all living organisms, to varying degrees, as intelligent. Autopoiesis stipulates life = cognition, and that emergent life forms will eventually be constructed by humans. Thereby, a baseline for defining that all living species are intelligent is established. That baseline enables us to distinguish between microbe, plant, animal, and AI intelligence in discussions recognizing varying types of cognition, diversity, and safeguards they entail. This is particularly important because it recognizes distributed intelligence in non-neurological organisms such as bacteria and plants and thereby becomes a vehicle for bioAI (technology) to meet cellular life as equals.

Between Hamburg and Brussels two Intelligent Beehives straddle physical/phenomenal life where inanimate matter and intelligence meet and generate forms and agency . . . debate and questions. For example: How can architects transfer and program intelligences from organisms and/or AI for environmental bioremediation? And, once transferred: How can architects design to activate living organisms where machine/bacteria ingest pollution as nourishment for their building's energy supply? Such questions rapidly become self-referencing when public debate, design teams, urban planners, or classes need to consider biological tasks carried out by associations of microbes and AI. In this framework, a building could, among many other things, be assigned to monitor passive ventilation, maximize photosynthetic exposure, and/or metabolize CO_2 with onboard microbial agents.

What is then defined as biointelligent performance extends research and case study operations to ontological ways of being/thinking for metabolic art and architectures in urban/natural systems. It generates questions normally asked in biology, plant, and material sciences for understanding how organisms thrive; create community, and signal/communicate with each other (e.g. bee language or biofilm cities). In those steps, AI-microbe hybrids involve theoretic logic for simulating and/or prototyping behavior activating cells implanted or hybridized into a building's infrastructure or façade walls. Cellular actions might also take place in manners modeled on a leaf's production of photosynthesis (natural or artificial photosynthesis); or through a bacteria's enactment of biochemical homeostasis. Both microbes and AI are enmeshed as metabolic scaffolding/agency supporting networked façade-to-interior performance and thus establishes a new kind of living morphology developing in the Hamburg hive (metaphorically) in

the shadows Hambourg's BIQ Building.

Close observation by Maes includes instrumented images of functions in nature (e.g. electron microscopy/CT scanning) suggests visualized morphology scaled to embed cellular agents — microbes, plants, and AI — as monitors to address climate change with living and/or bioAI organisms. Those observations presuppose subsystems and sub-subsystems provisioning and nourishing aggregate behaviors between machines, microbes, and AI. Linked to research — thinking-to-biology, biology-to-code, and code-to-prototype[25] — exercises species' cognition and our notions of machines rooted in AlanTuring's[26, 27] bio-tinged question: "Can machines think?" From "Can machines think" I extrapolate and ask: Can buildings/sculpture remediate pollution? The new question presupposes a building's or sculpture's intelligence enabling, for example, bacterial life feeding on carbon dioxide ($CO_{2)}$ converting toxins in ways pioneered by oil-spill cleanup.

Today, constructed species of AI and ALife[28] extend Turing's above question. Answered positively, it gives credence to the proposition: Buildings can think. Thereby, generalized research goals emerge from realms of theory and art that justifying science/technology and architecture extending life functions from hives to machines/buildings. As the *Hamburg Machine* establishes in the junctures between human intelligence, technology, nature, and art — another question arises: Can AI think it is alive? If so, autopoietic structures such as *ElbBienen* emerge as symbiotic-biomachinic prototypes contemplated to transmit nature's coded/decoded instructions for the operation of buildings entering zones of autonomous ecological remediation.

If an intelligent-metabolic design OS sounds like science fiction — that's good — it portends a future where AI and design's biology/cognition are contemplated as design aspects of human-extended-phenotypes identifiable as units of nature. Once a method of thinking about living biotechnology is theoretically usable and publically agreed upon, it may logically proceed. New iterations of AI — biological, synthetic, and hybrid — are in development in laboratories around the world. Plant intelligence predicated on sensing, signaling, and biochemically reacting are equally subjects of international research.[29]

Theory and prototyping for metabolic buildings should recognize that collective bio/AI intelligences impact near-future fabrication, materialization, and expectations for metabolic architectures and cities. Hives now enliven the *Hamburg Machine* as it engages the public to discuss responsive systems, protocols, and methodology for joining sustainability and living technology[30] to proactively unite in cities and nature. Those discussions include cohabitation between organisms in wild/urban nature devoted to eradicating toxic pollution and conducting ongoing environmental monitoring and endangered species preservation.

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