Design com "matéria viva": características de artefatos de biodesign de acordo com a literatura

Design with "living matter": characteristics of biodesigned artefacts according to the literature

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Resumo

É sabido que fazer design com outros seres viventes, implicando em "matéria viva", é diferente do que projetar com cerâmica, metais e polímeros. Esta prática tem o nome de biodesign, um termo polissêmico. Neste trabalho busca-se responder a três perguntas de pesquisa: (i) Como os artefatos de biodesign são caracterizados na literatura?; (ii) Quais são as formas de vida com as quais designers estão trabalhando em suas pesquisas de design?; e (iii) Quais são as aplicações que estão sendo planejadas para a "matéria viva"? Como estratégia metodológica revisita-se uma revisão sistemática bibliográfica com uma amostra de 48 trabalhos. Para estudos futuros recomenda-se uma busca para além da literatura científica, como em iniciativas públicas e privadas.

Palavras-chave: Biodesign; Materiais Vivos; Aplicações.

Abstract

It is well known that designing with other living beings, involving "living matter", is different from designing with ceramics, metals and polymers. This practice is called biodesign, a polysemic term. This work seeks to answer three research questions: (i) How are biodesigned artefacts characterised in the literature? (ii) What are the lifeforms that designers are working with in their design research? and (iii) What are the applications that are being planned for "living matter"? The methodological strategy consisted in revisiting a systematic literature review with a sample of 48 works. For future studies, a search beyond scientific literature is recommended, such as in private and public initiatives.

Keywords: *Biodesign; Living Materials; Applications.*

1 Introduction

Biodesign is a polysemic word that refers to "[…] design and design research which use living systems as part of their production and operation" (Dade-Robertson, 2021, series introduction note) - among other meanings which will not be addressed here. Some authors like Camere and Karana (2018) explain biodesign as design with "living materials", which means that designers work with matter that is alive. An example of biodesign is the process of Modern Synthesis, they grew bacteria into woven structures and made a shoe (Modern Synthesis, 2021). Another example is the Reef Design Lab process, they 3D printed calcium carbonate structures to be fulfilled by the growth of corals (Reef Design Lab, 2021). Figure 1 presents the two examples.

Figure 1 – Biodesign examples

Source: Reef Design Lab (2021); Modern Synthesis (2020)

Biodesigning would be reportedly different from what designers are used to. Antonelli writes "It goes without saying that when the materials are not plastics, wood, ceramics, or glass, but rather living beings or living tissues, the implications of every project reach far beyond the form/function equation and any idea of comfort, modernity or progress" (2018, p.7). Dade-Robertson (2021, p. 95) reinforces such perspectives: "You can't master life in the way a painter masters oils or a joiner masters wood".

Biodesign testifies the will to include other lifeforms in our day-by-day (Vettier, 2019). But (i) how are these biodesigned artefacts characterised in the literature? (ii) What are the lifeforms that designers are working with in their design research? (iii) What are the applications that are being planned for "living matter"? To address these questions, this paper revisits a systematic literature review. The following sections show the methodologic strategy used to review the literature, the findings, finishing with the discussion and conclusion, proposing topics to further develop biodesign research.

2 Methodological Strategy

The strategy was to revisit a systematic literature review performed in 2020 looking for the answers to this paper's research questions. The detailed procedures are described in the thesis "Design with the Living: Learning to work Together" (Strobel do Nascimento, 2023, pp. 102-103, pp. 112-127). For the analysis of the sample of works a table was built, organizing the references, the lifeforms that the authors worked with, and the applications.

To give an overview of the original process, the selected databases were Thomson and Reuters' Web of Science (WoS) and Elsevier's Scopus - using six search strings: "biofabrication" AND "design"; "growing design"; "living materials" AND "design"; "growing materials"; "biogenic materials" AND "design"; "material driven design"; "biodesign" AND "organism"; "biodesign" AND "material". No time restriction was made and the search was performed considering the paper's title, abstract, and keywords. The filter application followed an open reading strategy, reading the whole paper when necessary. The exclusion criteria were:

(1) theme disambiguation – when the paper was not related to the biodesign concept according to Dade-Robertson`s definition (2021);

(2) studies only considering materials testing, construction, and characterisation in a strict technical manner, not offering product design applications;

(3) strict definition of living matter morphogenesis.

In addition to the resulting papers after the filters, the sample included publications from two research laboratories: MIT Mediated Matter Lab and TUDelft Material Experience Lab.

3 Findings

To recall the literature review process, the two consulted databases rendered a total of 1347 entries through the six search strings. The exclusion criteria filtered 43 relevant results, of which 4 could not be accessed, hence 39 papers. Most of the entries were narrowed down by exclusion criteria 1, theme disambiguation. This reinforces the polysemic nature of the concept of "biodesign", which, according to the entries, is mostly used in biomedicine, referring to the artificial development of organs, for instance. Meanwhile, 9 papers were added from MIT Mediated Matter Lab and TUDelft Material Experience Lab. These results composed a final sample of 48 papers. The sample is characterized by conference papers, editorials, and journal papers published between 2011 and 2020. Although no time restriction was determined, 25 of them (more than 50%) were from 2018 and on, suggesting that the term biodesign is being more widely applied to design with other living organisms since then.

Replying to the research question (i) how are biodesigned artefacts characterised in the literature? - what was retrieved from the sample on this matter was summarized in the following paragraphs. It was possible to notice that most studies refer to the living material characteristics themselves and not to the final designed products.

The first characteristic of biodesigned artefacts must be the living quality of the material in the design. This seems not to be consensual among researchers, as some authors deactivate (kill) the organisms after the production process and some aim to have the living systems alive throughout the product's use.

On keeping the organism alive during the product's lifetime, Liu et al. (2017) detail that the artefact must be possible in terms of nutrition and living conditions for maintaining viable and functional cells in the long term. This would still be a challenge, especially when some exchange must be made with the environment, as it is the case of organisms that would need oxygen, for example. Many hydrogels and elastomers which might be infiltrated with nutrients are being developed and tested to create these necessary conditions (Liu et al., 2017). The main concern in these cases is maintenance. Structures are also being studied, such as optimal shapes, cavities, and sizes to accommodate the organisms into the artefacts, allowing a connection to obtain oxygen or light from the environment when needed (Mogas-Soldevilla et al., 2015; Bader et al., 2016; Liu et al., 2017; Schaffner et al., 2017; Moser et al., 2019; Zolotovsky; Gazit; Ortiz, 2018). This effort to maintain the organism alive and "functioning" seems to be a common endeavour in studies that 3D print bacteria, but there are also experiments with fungi. For example, Gerber et al. (2012) produce a system to evaluate the possibilities of self-cleaning surfaces with living *Penicillium roqueforti*.

The other approach would be to maintain the organism in a "deactivated" or dormant state after the object is considered finished, this is the case in bacterial cellulose (Zolotovsky, 2012) and mycelium-based materials (Attias et al., 2019). In these cases, when the production process is ready, the pieces are put to dry out.

However, Zolotovsky (2012) described in a bacterial cellulose experiment that a small fraction of the organisms was kept alive even after the material was dried out - and it continued to grow and reproduce when the nutrition and growing conditions were available again. The author observed "self-healing" in her experiment (a tear on the bacterial cellulose was mended by the bacteria) and she sees this as an opportunity to experiment with the organism's response to stimuli (Zolotovsky, 2012). So "self-healing" and "mendable" could be mentioned as possible characteristics of a biodesigned artefact, given the adequate conditions.

Regarding the aesthetic and experiential qualities of biodesigned artefacts, they are reportedly different from the consumers' usual repertoire - which is being viewed as a challenge to market acceptance by some authors (Camere; Karana, 2018; Karana Et Al., 2018; Keune, 2017). For example, "living materials" have a specific smell (Camere; Karana, 2018; Karana Et Al., 2018; Keune, 2017). Also, biodesigned materials also change and people would not be used to domestic products that would change with seasons, for instance (Keune, 2017). Keune advocates that "living materials" invite a reflection on the cultural and aesthetic bias toward natural processes in interior scenarios, what Dew and Rosner (2018) would call the "diachronic properties of the materials". Instead of fixed properties, there would be a rather momentary stabilisation of the material qualities and a performative view of them (Dew; Rosner, 2018). Karana et al. (2018) advise that those unique experiential qualities should guide the design with "living materials". Ayala-Garcia and Rognoli (2017) also discuss aesthetics and descriptors for "living materials" in the context of the do-it-yourself category. The authors argue that industrial materials usually have uniform surfaces and an artificial aesthetic, while do-it-yourself materials tend to evidence the source from which they were obtained. They develop an aesthetic map containing attributes that describe sensorial and perceptive qualities of the materials. Divided into five "kingdoms", Kingdom Vegetabile (plants and vegetables) is characterized as "source-traceable", "rough", "uneven", "presents traces of decay", and its "degradability" is inherent. Other characteristics such as "expandable" and "cheap" were also listed for this kingdom. Kingdom Animale (animals and bacteria), in turn, was described as "malleable" and "flexible". Surfaces were also considered "uneven", but "elegant" (Ayala-Garcia; Rognoli, 2017).

Biodesigned products might also incorporate the special characteristics related to each organism's abilities. Some examples are mentioned in the literature, for instance, fungi species that are being studied for their resistance to radiation (Shunk; Gomez; Averesch, 2020); and bioluminescent bacteria (Kera, 2014).

Concerning the biodesigned artefacts' applications, and already partially replying to the research question (iii) What are the applications that are being planned for "living matter"? - Camere and Karana (2018) and Karana et al. (2018) discuss the application of growing design and growing materials and describe a trend of what they call (1) "demonstrators" and (2) "surrogates". The first application type, the demonstrators, would consist of archetypal objects, such as lampshades, chairs, and flower vases. Their purpose would be to make the material understandable through a simple known artefact (Camere; Karana, 2018). The second type would be the surrogates, which would be attempts to mimic other materials, their aesthetics, in order to be marketed as a more sustainable substitute. In this case, biodesigned objects are often viewed as a sustainable alternative to traditional materials, for example, mycelium to replace petroleum-based polymers (Camere; Karana; 2018 Attias et al., 2019; Antinori et al., 2020).

While the commercial application of "living materials" still faces some challenges, Dade-Robertson (2021) highlights the "Technology Readiness Level" (TLR) of biodesign for now. According to him, TLR was initially developed to grade NASA Research & Development projects for mission readiness and he states that: "We need to recognise that our research may reside for some time at TRL levels 1, 2, or 3" (Dade-Robertson, 2021, p.9). Those would refer to "1-Basic principles observed and reported; 2-Technology concept and/or application formulated; and 3-Critical function, proof of concept established" (Dade-Robertson, 2021, p.8).

To further explore research questions (ii) What are the lifeforms that designers are working with in their design research?, and (iii) What are the applications that are being planned for "living matter"? - Table 1 presents the distribution of applications per species found in the systematic literature review sample.

Table 1 – Application distribution according to authors

	Publication	**Life form**	**Applications**
1	Antinori et al. (2020)	Fungi (*Ganoderma lucidum)*	Alternative to polymers, buildings, textiles, electronics, biotechnology (micro and nanometric scale);
2	Appiah et al. (2019)	Microorganisms or independent tissues	Robots in healthcare applications, wearable sensors;
3	Attias, Danai and Abitbol (2020)	Fungi, (*Ganoderma lucidum* and *Pleurotus ostreatus*, *Ganoderma sp., Pleurotus sp., T. versicolor, Trametes sp.*)	Packaging (electronics, food), insulation (thermal and acoustic), alternatives to polystyrene-based materials, bricks, leather, interior and product design applications, floors and acoustic tiles, furniture, floating mats, architectural topology, agriculture (seeding), Jerrycan (insulated portable water container);
4	Attias et al. (2019)	Fungi (*Pleurotus ostreatus, Colorius sp., Trametes sp., Ganoderma sp.*)	Packaging, building and insulation materials, alternatives to leather, textiles and transparent edible films;
5	Ayala-Garcia, Rognoli and	Fungi, bacteria, plants, algae	-

	Publication	Life form	Applications
	Karana (2017)		
6	Ayala-Garcia and Rognoli (2017)	Fungi, bacteria, plants	-
7	Badarnah (2017)	Plants, algae	Architecture, adaptive buildings;
8	Bader et al. (2016)	Bacteria (*Escherichia coli, Bacillus subtilis*)	Functional living wearables;
9	Bernabei and Power (2016)	Fungi, oyster mushrooms	Furniture, chair;
10	Camere and Karana (2018)	Fungi, bacteria, plants, algae, protista (amoeba)	Furniture, clothes, footwear, water bottles, construction modules;
11	Camere and Karana (2017)	Fungi, bacteria, algae	Furniture, clothes, domestic utensils, packaging;
12	Cohen, Sicher and Yavuz (2019)	Fungi (*Saccharomyces cerevisiae*), bacteria (*Komagataeibacter xylinus*), a symbiosis of those species, algae	Clothes, sanitary pads, edible food packaging, food labels, plates;
13	Collet (2017)	Fungi	Slow-grown embellishments for fashion applications, textiles;
14	Collet (2020)	Fungi, bacteria, algae, protista (slime molds),	Textiles and fashion, shoes, furniture;
15	Dew e Rosner (2018)	Bacteria, algae, living cells	Woodworking, architecture, timber framing, human-computer interactions;
16	Gerber et al. (2012)	Fungi (*Penicillium roqueforti*)	Conceptual design of a material surface with self-cleaning capability when subjected to a standardized food spill, consumer goods such as packaging, indoor surfaces, biotechnology;
17	Gough et al. (2020)	Plants	Interactive systems;
18	Gumuskaya (2020)	Fungi, bacteria (*Sporosarcina pasteurii, Acetobacter xylinum, Escherichia coli JM2.300 strain*)	Self-constructing structures for architecture, bricks , furniture, textiles;
19	Karana et al. (2018)	Fungi (*Trametes, Schizophyllum Commune*)	An innovative packaging for (wine) bottles;
20	Kera (2014)	Fungi, bioluminescent bacteria, algae	Synthetic lamps;
21	Keune (2017)	Plants (corn)	Curtains, interior textiles;
22	Keune (2017)	Plants (corn, barley grass, lettuce)	Textiles;
23	Kirdök et al. (2019)	Fungi, bacteria (*Sporosarcina pasteurii, Bacillus pasteurii*), microalgae, animal (*Bombyx mori* silkworm, corals)	Architecture, structural and construction materials, bricks and building blocks, energy generators, digital storage systems, air purifiers, urban furniture, children's playgrounds, kiosks, exhibition stands;
24	Lazaro Vasquez and Vega (2019)	Fungi (Ecovative kit)	Wearable accessories with embedded electronics, necklace, headpiece tiara, bracelets;

	Publication	Life form	Applications
25	Lee, Lee and Kim (2018)	Fungi, bacteria (*Sporosarcina pasteurii*), algae	Architecture, building module to form "building skins" that could become habitat to wild bees;
26	Li et al. (2017)	Living cells	Medical applications, biorobotics;
27	Liu et al. (2017)	Bacteria (genetically modified *Escherichia coli*)	Living wearable devices, stretchable living sensors responsive to multiple chemicals, interactive genetic circuits, patch to sense chemicals on the skin, glove with living chemical detectors in the fingertips, low-cost chemical detectors, water quality alerts, disease diagnostics, and therapy;
28	Melkozernov and Sorensen (2020)	Bacteria, plants, animals, protista, (slime mold, *Physarum polycephalum*)	Textiles;
29	Mogas-Soldevilla et al. (2015)	Bacteria (*Escherichia coli*), Cyanobacteria	Lightweight robotics (flapping micro vehicles), biocompatible wearable devices in contact with regenerating tissue, biofuel producing bacterial culture supports, fully compostable consumables, ecosystem-enhancing constructs that replenish soils with nutrients as they decay, and temporary biodegradable architectural structures or building skins;
30	Monna (2017)	Fungi (Ecovative kit)	Community garden applications: birdhouses, bowls, garbage cans, chairs;
31	Moser et al. (2019)	Bacteria (*Escherichia coli*), Cyanobacteria	Wearable devices and clothes, materials that sense and degrade toxins, clothing that regenerates or inactivates volatiles in body odor, sentinel objects that survey for pathogens, nodes that use bacteria to generate power in place of batteries, bandages in which wound healing is managed by consortia, bacteria as adhesives;
32	Ottelé et al. (2011)	Plants (*Hedera helix*, Pterosida)	Architecture;
33	Oxman (2015)	Living cells	Furniture, architectural structures, wearables;
34	Oxman et al. (2014)	Animals (*Bombyx mori* silkworm)	Smart textiles;
35	Oxman et al. (2013)	Animals (*Bombyx mori* silkworm)	Architecture structures, fiber-based structures,
36	Oxman et al. (2015)	-	-
37	Parisi and Rognoli (2017)	Fungi (Ecovative kit)	Test samples;
38	Parisi, Rognoli and Ayala-Garcia (2016)	Fungi (Ecovative kit)	Bowls, packaging, furniture and insulation for architecture, vases, lamps, shoes, mats, surf-boards and buoys;
39	Pataranutaporn, Ingalls and Finn (2018)	Bacteria (*Escherichia coli*)	Morphable textiles, wearable technology, Bio-HCI framework, a compiler that converts image files (.JPEG) into DNA sequences, which can be ligated into a plasmid DNA that can be transferred into bacteria;
40	Sayuti and Ahmed-	Biological materials	Circumventive organs, bio-encryption, lung-on-a-

	Publication	Life form	Applications
	Kristensen (2020)		chip, microfluidic channels etched into a transparent polymer, human alveolus and endothelial cells, furniture;
41	Schaffner, Ruhs and Coulter (2017)	Bacteria (*Pseudomonas putida*, *Acetobacter xylinum*)	Biomedical and biotechnological applications, biologically generated functional materials;
42	Smith et al. (2020)	Bacteria (genetically modified *Escherichia coli*)	A biohybrid face mask featuring a prescribed biological response (i.e., colored patterning indicating locally tunable gene-regulated protein expression), topical therapeutic devices, consumer products, bandage-like prototypes, medical applications;
43	Vettier (2019)	Bacteria, plants, animals (bees)	Flower vase, traditional textiles;
44	Walker et al. (2019)	Bacteria (*Komagataeibacter rhaeticus*)	Biomedical and cosmetic applications, protective bandaging, electronics, self-repairing material;
45	Weiler et al. (2019)	Fungi (Ecovative kit)	Human-computer interaction devices, low-fidelity prototypes, temporary enclosures and replicas;
46	Yang, Gao e Xu (2020)	Living cells	Tissue engineering, drug delivery, wound repair;
47	Zhou et al. (2020)	Plants (oat)	Furniture;
48	Zolotovsky, Gazit and Ortiz (2018)	Bacteria (genetically modified *Gluconacetobacter xylinus*)	Medical applications, textiles, high performance acoustic materials. If the materials are kept alive: responsive robotic skins, solar cells, even photosynthetic building envelopes;

Source: Elaborated by the author (2021)

In summary, we may observe in the literature sample that biodesigned artefacts are characterised (research question i) by containing or being produced by organisms that are alive in the artefact or not. Furthermore, they could be self-healing or mendable. Aesthetically and experientially, they could have a specific smell, change in time, and they could have in them clear traces of the original source that produced them. Moreover, biodesigned artefacts could have special abilities that come from their original organisms, like resistance to radiation and bioluminescence.

Additionally, regarding research question ii, the lifeforms with which designers work with in biodesign according to this sample are found as such: 4 works cite animals (insects, more specifically), 22 mention a variety of bacteria, 22 mention fungi, 9 mention plants, 9 cite algae, and 3 mention protozoa.

Regarding their applications (research question iii) we may see that biodesigned artefacts might be qualified as demonstrators and surrogates, and that they are still in initial phases of the TLR scale. As shown in table 1 it is possible to notice a great variety of applications of biodesigned artefacts, from architectural purposes to packaging, textiles, wearable devices, etc.

4 Discussion

While revisiting the literature review for the research questions (i) How are biodesigned artefacts characterised in the literature? (ii) What are the lifeforms that designers are working with in their design research?, and (iii) What are the applications that are being planned for "living matter"? two interesting issues were raised that are discussed in this section.

Regarding the market acceptance difficulty for biodesigned artefacts expressed in the literature - contributing to build a better perception of what would be the "weirdness" of having living organisms in our daily artifacts, we could draw on art. Some artistic projects bring to light that humans are already home to whole microbiomes. The Human Microbiome Project is a five-year program that began in 2008 and researched the organisms living inside us, even the most difficult ones to trace (Myers, 2018). The artists demonstrate we already live with "living matter". Myers elaborates: "[…] The delicate balance of these intimate associations on which our lives depend is likely to alter our sense of self and our conception of the environments in and around us that teem with invisible life" (2018, p.205). Richard Beckett talks about a modernist antibiotic approach, or an antibiotic management of life, leading to a loss of particular microbes or loss of diversity (HBBE, 2021). In his talk "Probiotic Cities", he advocates a probiotic turn: "managing life, using life" (HBBE, 2021). Beckett discusses the ontology in the binary opposite concepts of human and non-human. A shift in the collective conscience regarding the perception of some "living materials", such as fungi, might be a challenge for designing with other living organisms for them to become more market-friendly. Despite the risks of mismatched perceptions regarding some "living materials", their potential for innovative and sustainable solutions stimulates research and development. The possibilities offered by some species with "special abilities", such as absorbing radiation, offer thrilling perspectives to product development (Shunk; Gomez; Averesch, 2020). Authors such as Camere and Karana (2018) present the argument for the contribution of "living materials" toward sustainability, remarking on their growth from byproducts of production streams, their low energy consumption for production, and their biodegradable characteristics.

Furthermore, about the two application trends described by Camere and Karana (2028), the demonstrators and the surrogates. Camere and Karana question if these applications are adequate choices according to the material's characteristics, which would face many challenges when effectively employed in a product, especially regarding durability. Ultimately, they suggest the unique attributes of "living materials" should be better valued and assessed within more suitable applications. Some companies are already doing this, for example, companies that market mycelium products are reportedly strategically adding value by arguing qualities of (1) sustainability and performance, as environmentally friendly replacements for other materials; and (2) a luxury market identity, highlighting therapeutic and spontaneous properties of the material (Parisi; Rognoli; Ayala-Garcia, 2016) – for their biodesigned products.

Finally, the next section presents the final considerations of this paper.

5 Final Considerations

Biodesign refers to the design practice involving other lifeforms, it implies designing with "living matter". It has peculiar implications on the design dynamics and it is a way of including others (other species) in our day-by-day. This paper investigates three research questions regarding biodesigned artefacts: (i) How are biodesigned artefacts characterised in the literature? (ii) What are the lifeforms that designers are working with in their design research? and (iii) What are the applications that are being planned for “living matter”?. The methodological strategy was to revisit a systematic literature review organized in 2020.

Results were sorted in a table, describing the authors, the lifeforms they worked with and the applications they biodesigned for.

For research question (i) – it was found that biodesigned artefacts could keep a lifeform alive while they are being used by humans, as well as they could have the lifeform deactivated after their production. Furthermore, they could be self-healing and mendable, they could have a specific smell in comparison to “normal products”, they could have their characteristics changed through time, they could have apparent characteristics of their original source, and they could have the special abilities owned by the origin lifeform.

For research question (ii) it was found that the sample provided mainly works with bacteria (22 works) and fungi (also 22 works). Other lifeforms mentioned were plants (9 works), animals (4 works), and protozoa (3 works).

Finally for the research question (iii), two were the application trends found in the literature: surrogates and demonstrators. The Technology Readiness Level for biodesigned artefacts is mostly 1, 2, or 3 – which means that most of them only reach the proof of concept level. A great variety of applications of biodesigned artefacts could be seen, from architectural purposes to packaging, textiles, wearable devices, etc.

Further research could be done searching for applications not mentioned in the scientific literature, such as those developed by public and private initiatives.

At last, it is worth mentioning that to place other lifeforms as materials is problematic *per se* - in stressing even further the dichotomy of human *versus* nature and treating other species as a resource to be manipulated. Further research in biodesign could reconsider the use of the “living material” concept and reinforce notions of care and respect (Williams; Collet, 2020). Williams and Collet (2020) also characterise biodesign as a “multispecies assemblage” – it is important for researchers to recognise their position of power to other species and to acknowledge that anthropomorphisation is inevitable.

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7 Checklist

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