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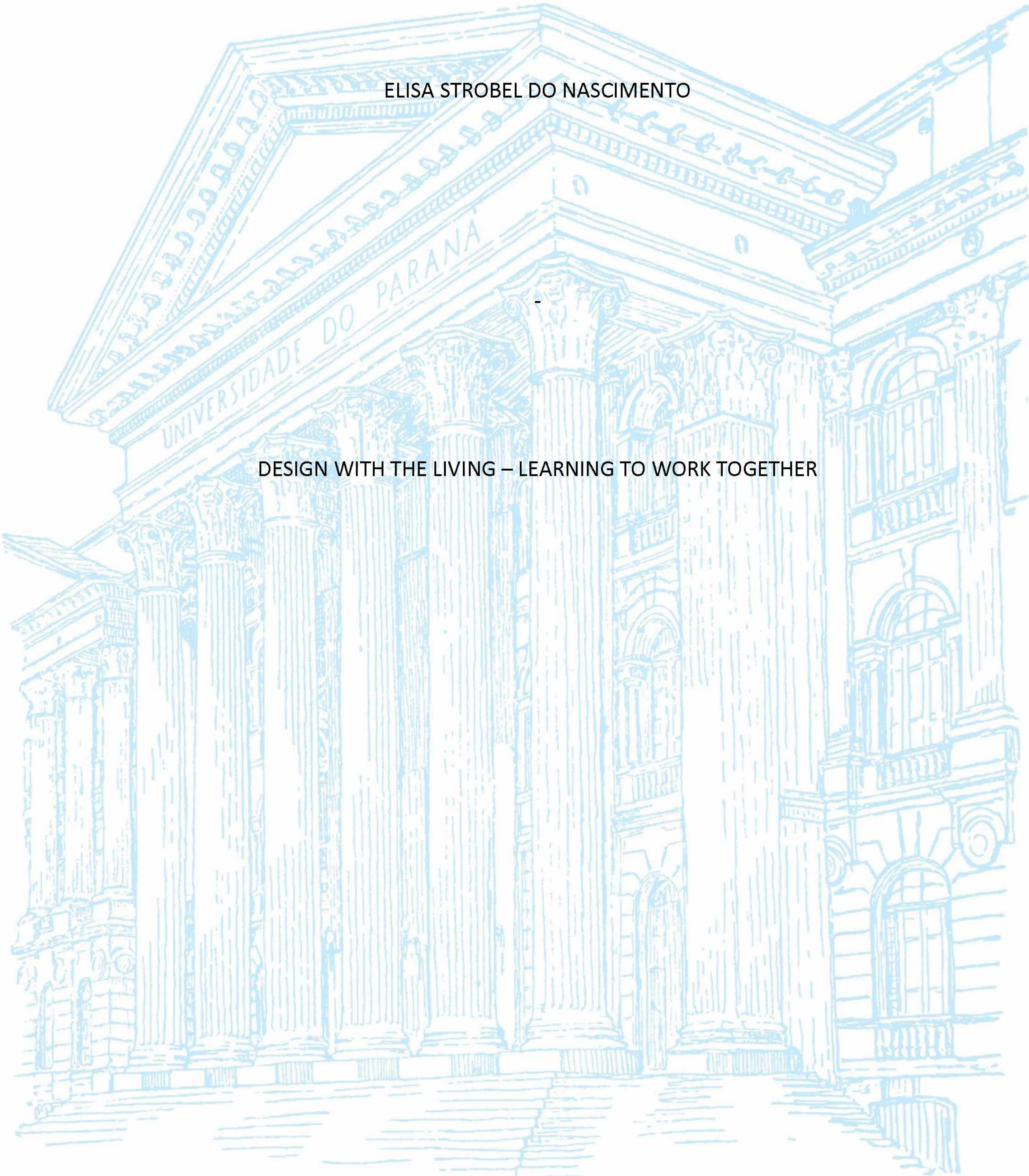

ELISA STROBEL DO NASCIMENTO

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DESIGN WITH THE LIVING – LEARNING TO WORK TOGETHER

CURITIBA

2023

ELISA STROBEL DO NASCIMENTO

DESIGN WITH THE LIVING – LEARNING TO WORK TOGETHER

Tese apresentada ao curso de Pós-Graduação em Design, Setor de Artes Comunicação e Design, Universidade Federal do Paraná, como requisito parcial à obtenção do título de Doutor em Design.

Orientador: Prof. Dr. Adriano Heemann
Co-orientador: Prof. Dr. Aguinaldo dos Santos

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“O resultado é que as plantas não têm rosto, membros ou, em geral, qualquer estrutura reconhecível que as aproxime dos animais, o que as torna praticamente invisíveis. Nós as consideramos uma mera parte da paisagem. Vemos o que entendemos e entendemos apenas o que é semelhante a nós. A alteridade das plantas depende disso.”

“As a result, plants have no face, limbs, or any recognizable structure in general that could bring them anything closer to animals, which makes them practically invisible. We consider them as a trifling part of the landscape. We see what we understand and we only understand what resembles us. The plant’s alterity depends on that.”

(MANCUSO, p.95, translated by the author)

RESUMO

A prática do biodesign parece estar se consolidando por meio de redes, concursos, exposições, e educação formal. Este estudo se baseia na definição de biodesign de Dade-Robertson, que compreende o design e a pesquisa em design que trabalhem com sistemas vivos como parte da sua produção e funcionamento. Assim, ainda numa perspectiva antropocêntrica de pesquisa, surgem novas possibilidades com as capacidades e características de várias espécies e as novas formas de construir e fazer. No entanto, vários desafios práticos e teóricos ainda limitam a difusão do biodesign. Uma lacuna parece ser a estruturação de um artefato de facilitação para o ensino e aprendizagem do processo de biodesign. A fim de contribuir para a mitigação desta lacuna, o presente trabalho procurou desenvolver e avaliar um framework para facilitar o ensino e a aprendizagem do processo de biodesign no ensino de graduação, considerando um contexto com poucos recursos, como a falta de um espaço para experimentação e um laboratório. A estratégia metodológica utilizada é a Design Science Research (DSR) conforme Dresch, Lacerda, e Antunes Jr. (2015). Esta estratégia foi adaptada às etapas: 1. Problema e Contexto; 2. Artefatos Relacionados; 3. Desenvolvimento; 4. Avaliação; e 5. Conclusão. O framework baseou-se na revisão da literatura, que inspirou 59 insights, que embasaram 17 requisitos que, por sua vez, foram estruturados em 21 objetivos de aprendizagem em acordo com a taxonomia de Bloom. O framework considera dois espaços de contexto: a sala de aula e as casas do(a)s estudantes. Ele é composto por 6 elementos principais: 1. Conceitos, 2. Repertório, 3. Metodologia de Projeto; 4. Prática; 5. Reflexões; e 6. Gestão. Exemplos das materialidades e atividades do framework são um diário de projetos e tinkering. Para além do framework, foram desenvolvidos artefatos de apoio: quatro modelos didáticos do processo de biodesign baseados em entrevistas semi-estruturadas com designers experientes - design em colaboração com (1) cogumelos, com (2) árvores, com (3) gramíneas, e com (4) bactérias. Os modelos basearam-se numa adaptação do Método Mosaico de Kim e Lee (2015), da Estrutura de Duplo Diamante do Design Council, e do Processo de Desenvolvimento de Produtos de Rozenfeld et al. (2006). A instanciação ocorreu na disciplina obrigatória Materiais e Processos III do curso de graduação de Design de Produto da Universidade Federal do Paraná. O framework foi avaliado por meio de observação aberta e da rubrica de avaliação do framework pela professora da disciplina e pelo(a)s estudantes. A triangulação e a correspondência de padrões com os objetivos de aprendizagem sugerem que 14 deles foram cumpridos, enquanto os outros 7 foram parcialmente atendidos. Ao longo do processo, o(a)s estudantes parecem ter desenvolvido novas sensibilidades em design, relacionadas com a empatia e as negociações com o outro organismo vivo com o qual trabalharam. Foi feita uma imersão no cluster de excelência "Matters of Activity". Image, Space, Material" para a discussão dos resultados. O framework deve ser testado em outros contextos. Como trabalho futuro, poderá ser desenvolvida uma versão modular para abrir as heurísticas de contingência a contextos mais amplos e diferentes tempos de aplicação.

Palavras-chave: Design de Produto. Design com Organismos Viventes. Processo de Biodesign. Ensino de Biodesign.

ABSTRACT

The biodesign practice seems to consolidate through organized networks, contests, exhibitions, and formal education. This study relies on Dade-Robertson's definition of biodesign, which comprises the design and design research that work with living systems as part of their production and operation. Thus, still on an anthropocentric research perspective, new possibilities arise with the abilities and characteristics of various species and new ways of building and making. However, several practical and theoretical challenges still set back the diffusion of biodesign. One gap seems to be the structuring of a facilitation artifact for teaching and learning the biodesign process. In order to contribute to mitigate this gap, the present work aimed to develop and evaluate a framework to facilitate the teaching and learning of the biodesign process in undergraduate education, considering a context with few resources, like the lack of proper space for experimentation and a lab. The methodological strategy used is Design Science Research (DSR) following Dresch, Lacerda, and Antunes Jr. (2015). It was adapted into the steps: 1. Problem and Context; 2. Related Artifacts; 3. Development; 4. Evaluation; and 5. Conclusion. The framework drew on the literature review, which inspired 59 insights. The insights grounded 17 framework requirements, which in turn, rendered 21 learning objectives developed according to Bloom's taxonomy. The framework considers two context-spaces: the classroom and the student's homes. It consists of 6 main elements: 1. Concepts, 2. Repertoire, 3. Project Methodology; 4. Practice; 5. Reflections; and 6. Management. Examples of materialities and activities in the framework are a project journal and tinkering. Besides the framework, other support artifacts were developed in the research process: four didactic models of the biodesign process based on semi-structured interviews with experienced designers - design in collaboration with (1) mushrooms, (2) trees, (3) grass, and (4) bacteria. The models drew on an adaptation of Kim and Lee's (2015) Mosaic Method, the Design Council's Double Diamond Framework, and the Product Development Process from Rozenfeld et al. (2006). The instantiation occurred in the mandatory course Materials and Processes III of the Product Design undergraduate program of the Federal University of Paraná. The framework was evaluated through overt observation and through the framework's evaluation rubric by the course professor and by the students. Triangulation and pattern-matching to the learning objectives suggested that 14 learning objectives were met, while the other 7 were partially met. Throughout the process, students seem to have developed "new designerly sensibilities", related to empathy and negotiations with the other organism they worked with. An immersion was made at the Cluster of Excellence »Matters of Activity. Image, Space, Material« to discuss the results. The framework must be further tested in other contexts. For future work, a modular version of the framework might be developed to open its contingency heuristics to broader contexts and different application times.

Keywords: Product Design. Design with the Living. Biodesign Process. Biodesign Teaching.

FIGURES

TABLES

LIST OF ABBREVIATIONS

DIY	- Do-it-Yourself
DwL	- Design with the Living
MoA	- Cluster of Excellence “Matters of Activity. Image. Space. Material”
UFPR	- Federal University of Paraná

TABLE OF CONTENTS

“Instinctively we feel that there is something different about life”

(DADE-ROBERTSON, 2021, p.14)

1 INTRODUCTION

This thesis looks into the teaching and learning of the biodesign process (or the design with the living process) in undergraduate product design education. Through a systematic literature review (see justification), it was found that a framework for teaching and learning the biodesign process was not yet structured. This was the starting point of the research. This chapter outlines and introduces the research, its context, limitations, and motivations – Figure 1 presents the chapter's overview.

Figure 1 – Introduction chapter overview

Chapter overview

1. Introduction | 2. Design with the living concepts, and practice | 3. Methodological strategy and procedures | 4. Lessons on the biodesign process | 5. Discussion | 6. Conclusions | Appendix

1.1 Key Definitions
1.2 Context
1.3 Research problem
1.4 Aim and objectives
1.4.1 Specific objectives
1.5 Research scope and limitations
1.6 Justification
1.7 Methodological strategy overview
1.8 Thesis structure overview

Source: Illustrated by the author (2023)

1.1 KEY DEFINITIONS

There are several terms and concepts used to describe the design practice in collaboration with non-human living organisms, like design with "**living materials**" (CAMERE; KARANA, 2018), "**biodesign**" (MYERS, 2018), and "**biofabrication**[1]" (CAMERE; Karana, 2017). The Master's Program in Biodesign at the University of Arts London (MA Biodesign UAL) includes: "**biophilic** design, **bio-integrated** design, **biomimetic** design and **bio-informed** design" (UAL; 2022). Vettier uses the term "**objet vivant**", or living object (2019). Tamminen

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[1] See Glossary.

and Vermeulen called them "**bio-objects**" (2019). As terms widely vary, Camere and Karana (2017) eventually reported a "lack of a clear vocabulary" and a "confusion with other approaches that merge biology and design" (CAMERE; KARANA, 2017, p. 102).

Myers defined the term "biodesign" in his seminal book "Biodesign. Nature, science, creativity." in 2012[2] as: "refers specifically to the incorporation of living organisms or ecosystems as essential components, enhancing the function of the finished work [...]" (2018, p.8). After his book, this term was largely adopted by other researchers, such as Bernabei and Power (2016), Keune (2017), Collet (2017, 2020), Lee, Lee, and Kim (2018), Pataranutaporn, Ingalls and Finn (2018), Cohen, Sicher, and Yavuz (2019), Kirdök et al. (2019), Vettier (2019), Gough et al. (2020), Melkozernov and Sorensen (2020), Sayuti and Ahmed-Kristensen (2020), Zhou et al. (2020) and Dade-Robertson (2021). Vettier remarks that biodesign seeks to make living organisms essential to the composition of objects – whether in a structural manner, whether as a tool, whether in new product functions or with a broader sustainability-driven intention (VETTIER, 2019).

At the same time that the word biodesign seems to have been widely spread in the design community, the MA Biodesign UAL explains that there is no such thing as a universal definition for biodesign (UAL; 2022). Indeed, it is important to note that there are other uses for the term "biodesign" – it is often applied to refer to biomimetic and biomimicry principled designs (POLITES, 2019) and biomedical and biotechnological innovations (YOCK; ZENIOS; MAKOWER, 2015). Even the Biodesign Challenge, an international yearly competition and a reference in biodesign, seems to have a broader understanding of biodesign: defining a "biodesigner" as "an innovator at the intersection of art, design and biology". (BDC, 2021b). The MA Biodesign UAL's specific understanding of biodesign is "[...] as a means to incorporate the inherent life-conducive principles of biological living systems into design processes – to transition into a more holistic, sustainable future" (UAL, 2022, p.7). This definition also seems to be broader than Myer's, as presented earlier in this section.

In this brief analysis, it is possible to notice that the term "biodesign" might bring some controversy, as well as the variations "biodesign process" and "biodesigned products" – as it is understood that a "biodesign process" is also a "design process". In this thesis,

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[2] First edition in 2012. The edition consulted and referenced in this thesis was published in 2018.

biodesign follows Dade-Robertson's definition: "[...] **design and design research which use living systems as part of their production and operation**" (2021, series introduction note). This definition seems to be in line with Myer's definition. The term biodesign is used here in this sense, along with interchangeable more descriptive alternatives - which due to the confusion that the biodesign term rises, are preferred: "**design in collaboration with other living organisms**" and "**design with the living (DwL)**". This last expression might be attributed to the Design Museum's annual Symposium "Design with the Living" (DESIGN MUSEUM, 2020; 2021).

One last consideration to be acknowledged before beginning is that this research intention still lies in an anthropocentric perspective of science because it still thinks in means to operationalize collaboration with living organisms in terms of a useful resource. But the hope is that it leads to a **respectful conscience and way of treating living organisms**, and a more ecocentric attitude toward design (MELKOZERNOV; SORENSEN, 2020). This is also why the term **collaboration** is used to describe the relationship of the designer with the other living organisms, following other authors (COLLET, 2013; BERNABEI; POWER, 2016; KIRDÖK et al., 2019; GOUGH et al., 2020).

1.2 CONTEXT

Design in the intersection with nature seems to be a long-term pursuit. Since the 20th[3] century, **bionics, biomimetics, and biomimicry** have developed thinking and theory as the three representative biologically informed disciplines (IOUGUINA et al., 2014). Since biomimicry principles suggest **we should look at nature as a model, a measure, and a mentor**, Iouguina et al. (2014) argue that such perspective is the most holistic among the three disciplines. Benyus (2002) explains that seeing nature as a model means being inspired by its solutions. When nature is the measure, we must challenge ourselves to make decisions

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[3] Iouguina et al. (2014) review the historical background of these three concepts. All of them are built on precedent pieces of research and developments. According to the authors, Jack Steele would be responsible for the emergence of the term "Bionics" in 1960, deriving it from "Biology" and "Technics". Otto Herbert Schmitt would be the protagonist in the popularization of the term Biomimetics, a combination of "Bio" and "Mimesis", in 1969. Biomimicry became popular with Janine Benyus's publication in 1997.

considering its standards. To be mentored by nature means we ought to learn from its 3,8 billion years of experience (BENYUS, 2002). A fourth approach, biodesign, which has a lot in common with biomimicry's ontology and axiology, suggests to also **looking at nature as a coworker and a hackable system** (COLLET, 2020).

Examples of DwL practice include works with different species, from bacteria to animals. For instance, the company Fullgrown shapes living trees into furniture through horticultural techniques (FULLGROWN, 2021); Modern Synthesis weaves bacteria into shoes (MODERN SYNTHESIS, 2020); the Blast Studio develops 3D printed mycelium modules to compose objects such as lamps and columns (BLAST STUDIO, 2020); The Reef Design Lab develops 3D printed calcium carbonate structures to be collaboratively fulfilled with corals (REEF DESIGN LAB, 2021). Some of these examples are illustrated in Figure 2.

Figure 2 – Design with the Living (DwL) examples

Source: From left to right: Fullgrown's chair production (MATERIAL DISTRICT, 2018). Modern Synthesis' microbial woven shoe (MODERN SYNTHESIS, 2020) and Blast Studio's 3D printed mycelium lamp shade (BLAST STUDIO, 2020)

Contributing to build a better perception of what would be the "weirdness" of having living organisms in our daily artifacts, 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. According to Vettier, biodesign testifies the will to include other life forms in our day-by-day (2019). A shift in the **collective conscience regarding the perception** of some living materials, such as fungi, might be a challenge for designing in collaboration with other living organisms in order 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 (R&D). 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 (2018a) present the argument of the contribution of living materials toward sustainability, remarking their growth from byproducts of production streams, their low energy consumption for production, and their biodegradable characteristics.

The innovative perspectives and the reflections provoked in biodesign are themes of **exhibitions** in renowned museums – namely, "Alive, new Design Frontiers" at Fondation EDF (COLLET, 2013); more recently, "Mutations Créations – La Fabrique du Vivant" at Centre Pompidou (BRAYER; ZEITOUN, 2019); and "Material Ecology" at MoMa (MOMA, 2020).

Biodesign, design with the living, is reportedly **not only made by designers and universities**. Kera (2014), Camere and Karana (2018a), Damsin (2019), Attias, Danai, and Abitbol (2020), and Melkozernov and Sorensen (2020) stress the importance of do-it-yourself (DIY) online communities, within private and independent initiatives. **Universities, independent labs, companies, artists, designers, scientists, and DIY online communities share** exhibition spaces and authorship in scientific papers. Illustrating such a collaboration, in "Digital biofabrication to realize the potentials of plant roots for product design" the artist Diana Scherer cooperates with researchers from TUDelft (ZHOU et al., 2020). According to Myers this community convergence of the "expert with the amateur" brings to the practice an ethos of independence (MYERS, 2018, p.9). **This collaboration is resulting on a gradual consolidation and dissemination of increasingly robust theories, methodologies and**

practices.. Furthermore, the consistency of specific **competitions** suggests that biodesign is not an ephemeral trend, like the "Bio Art & Design Award" (BAD, 2021), since 2011, and the "Biodesign Challenge" itself, since 2016. The subject also features **events**, like the annual Biofabricate summits (BIOFABRICATE, 2021), the "Design with the Living" annual Symposium (DESIGN MUSEUM, 2020), and "Still Alive" (STILL ALIVE, 2020).

In fact, we might have always been "biodesigning", Dade-Robertson writes that:

> [...] in reality, very little in the biological world now exists without human intervention, and years of selective breeding have created new and strange species of dogs and cats to roses, which exist because of human preferences and 'design' rather than evolutionary necessity (DADE-ROBERTSON, 2021a, p.95).

Even so, developing products with living materials seems to be still considered an **experimental engagement** (CAMERE; KARANA, 2018).

Myers argues about the affordability of biotechnology tools and processes and the urgency of ecologically coherent practices converge to biologically informed practices. Myers declares "**Building with bacteria and other organisms is simultaneously becoming a technological possibility and a necessity**" (MYERS, 2018, p.16). Some authors speculate that the approximation to **biology could mark the design practice of the 21st century**. Collet writes that "the beginning of the twenty-first century marks a strong shift towards the amalgamation of the binary code (1s and 0s) with biological systems" (2020, p.1). She sees a shift in the role of design "from working with inanimate matter such as plastic and metals to making with animate living entities such as mycelium, yeast and bacteria" (COLLET, 2020, p.1). In the same way, Myers ponders: "Should biodesign be the next design paradigm [...] The spread of biodesign promises to be much like mechanization in the 20th century [...]: upending accepted practices, [...] and shaping an alien way of life" (MYERS, 2018, p.17).

Considering this context, it appears to be important to prepare designers to be able to navigate the practice of biodesign. The next section details the research problem and its scope.

1.3 RESEARCH PROBLEM

This section underlines several issues that build up and characterize the research problem, with arguments supported by the lliterature review

Designing with the living is reportedly different from what designers are used to. Antonelli (2018, p.7) writes that “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”. Dade-Robertson (2021a, p. 95) reinforces such perspectives: “You can’t master life in the way a painter masters oils or a joiner masters wood”.

Beginning with the **ethical implications** that arise and are discussed when designing, artists and designers question the transformation of a living being into a mechanism (VETTIER, 2019). Brayer (2019), Bianchini, and Quinz (2019) bring to attention the concept of **maintenance** in art, and how artists perform rituals with living artwork, rituals to feed and even kill it. Hence, bioart and biodesign have been walking hand in hand (MYERS, 2018). Bringing the reflection artists are making to industrial and product design seems valid: designers working with living materials must plan the object’s survival and its interaction with the user. How do we instruct the user to “take care”, or even “kill” the object? Who gets to decide what lives its independent life, what becomes an object, and what can die? Ethical implications arise in ontological and axiological discussions and also contribute to the **intellectual property debate** “How are we to manage the ownership of life’s materials?” (GINSBERG et al., 2014, p.xi).

Ethical implications are delicate in themselves, but the design process with the living, or the biodesign process, has many difficulties and challenges which reflect on the research problem in this thesis, like: collaboration with other scientists; a scientific lexicon; the nascent state of the biodesign field; the consequences implied when materials have agency, the lack of available information; the difficulties for scalability and feasibility; changes in design tasks and activities - like concept and formal expression possibilities and prototyping; and the new “designerly sensibilities” needed to design with living organisms (CAMERE; KARANA, 2018).

Cho (2018) notes some issues professionals usually face: (1) the **diplomatic reach out** to scientists, biologists, and bioengineers to seek collaboration; (2) the keeping of **effective**

communication throughout the project - to this topic, Myers (2018) points out the need for a **shared vocabulary**; (3) to **manage the collaboration** - in that respect, Myers also points out "**conflicting working styles and standards**" (2018, p.14); (4) Cho proceeds commenting that "working with new biotechnology is difficult, because of its **nascent state**" (2018, p. 266); and finally, he adds that living materials are (5) **fragile** and "**temperamental**".

This last quality is often referred to by other authors as the "**material's agency**" (CAMERE; KARANA, 2018), which brings a whole spectrum of challenges to the table. Gough et al. (2020, p.390) advocate design will have to go beyond human-centered perspectives: "[...] When components of an interactive system are living the designer will be required to co-create a product that allows the participating organism to thrive". How does the **design process** unfold in these circumstances? How could designers conciliate user-driven and living material-driven perspectives?

Furthermore, material agency seems to become a key characteristic that affects **predictability**, results in spontaneous developments, challenges control and the design intention. Zolotovsky (2012) and Collet (2020) report **unpredictability** and difficulty to control the product outcome. Dade-Robertson points out that "Designing the natural still requires us to develop methods and to anticipate outcomes which are unpredictable" (2021, p.26). Predictability is desired in a project and is targeted since its briefing. Knowingly, designers estimate time, costs, quality, risks, and requirements (PHILIPS, 2007). However, Bianchini and Quinz (2019) remark that life does not always follow the model. Collet (2019) demonstrates through an experiment, how **spontaneous developments** of mycelium create flower patterns on a rubber-like structure. She discusses how designers must develop strategies to enable more **controllable and predictable project environments**, but also to think about how to **negotiate the design intention** with the living organism responses (COLLET, 2017). Myers questions if full control is possible at all: "Can designers learn to empathize with other forms of life and surrender a small amount of control of their work to them?" (MYERS, 2014, p.9).

Unpredictability is not the only quality related to the material agency, but also all qualities that are inherent to life. Brayer makes a literature review about some characteristics of the living: (1) the ability to adapt; (2) the epigenetic dimension; (3) the aforementioned indetermination, unpredictability and morphological fluidity; and (4) **the irreversibility in time** it surpasses (BRAYER, 2019, p.60). Concerning this last quality, some authors and designers refer to 3D printing with living materials as “4D printing”, alluding to time as the **fourth dimension** (LI et al., 2017; YANG; GAO; XU, 2020). Dew and Rosner (2018) also elaborate on how designers must think of two-dimensional drawings in a four-dimensional world. Working with materials with an agency of their own might demand that designers think of how the design process and the designed artifact relate to time and change.

Another reported issue that might make it a challenge for designers to work with living materials, is the, although abundant, **scattered and incomplete data and information** available. When available, it quite often deals with a restricted production perspective. For instance, Attias, Danai, and Babitol (2020) describe difficulties in finding complete data to systematically reproduce experiments with mycelium materials in scientific literature. The authors speculate that patents and industrial property might be one of the reasons researchers might not be fully disclosing their material developments. Many authors emphasize the importance of looking into other sources besides scientific literature because some techniques and practices are described by independent researchers, companies, and community forums (DAMSIN, 2019; ATTIAS; DANAI; ABITBOL, 2020; KERA, 2014; MELKOZERNOV; SORENSEN, 2020).

While some authors present the difficulties that arise inherently to the material’s “livingness”, others focus on the achievement of commercial **scalability** for these technologies. It looks like much work is yet to be done to improve material **feasibility** and commercial potential (DAMSIN, 2019; ATTIAS; DANAI; ABITBOL, 2020; HARMON; FAIRBOURN; THIBAULT, 2020; STROBEL et al., 2021). Collet questions: “How can we then incorporate living dynamic qualities into our production systems?” (COLLET, 2017, p.34). As described before, biodesign is still considered experimental and in a nascent state. Antonelli notes that “[...] biodesign remains a burgeoning industry that would benefit from increased **public support** and financial resources if it is to become truly viable at a global scale” (2018, p.7).

Considering the **conceptual biodesign process**, authors expect that biodesign could **unlock** (a) **new product functions**; (b) **the work of designers in other scales - such as micro and nano**; (c) and **a whole new formal expression**. In the 21st century, Myers (2018) writes, there are new expectations for the product’s performance, in a broader concept of functionality. For this author, when designing at a cellular level, we might be enabling new design possibilities, comparable to those of what the millimetric scale opened in the Industrial

Revolution (2018, p.14). Marketing and acceptability concerns regarding living materials were previously mentioned in the context section. Camere and Karana (2018a) reinforce that living materials do have different qualities than those of traditional materials, such as a characteristic smell. Besides new aesthetics at a material level, Myers also foresees the emergence of a **"legible formal language" in biodesign** (MYERS, 2018, p.14).

Still concerning changes in the biodesign process in comparison to a traditional design process, **prototyping** seems to become a crucial activity that happens very early in the project development. Parisi and Rognoli (2017), Camere and Karana (2018a), and Karana et al. (2018) describe a "Material Tinkering" step, a form of prototyping that consists mostly of **growing** experiments to get to know the organisms' possibilities and limitations. Collet, in a similar approach, writes "What I can not grow, I can not understand" (2020, p.6). However, the Design Council reports that product-based companies try to "[...] reduce the number of physical prototypes required [...]" (DESIGN COUNCIL, 2007a, p.20) and also use virtual prototyping, simulations, and analysis to reduce costs (DESIGN COUNCIL, 2007a). Since design with the living is so different, it seems important to get to know how designers implement prototyping strategies in their design process with the living. Do they use virtual prototyping and simulations? How is prototyping managed to help reduce project development uncertainty? **To Collet (2020) growing would now be part of the design process, which impacts form, structure, aesthetics, and material specification.** This creating and controlling, she argues, brings to light new competencies to the designer besides the traditional methods they would be used to.

Camere and Karana (2018a) refer to these new skills and competencies as the "**new designerly sensibilities**". Additionally, Myers (2018) points out that the complexity of the tasks of form generating while designing with the living would demand "the observational tools and experimental methods of the life sciences" (2018, p.11).

Considering this problematic, this study focuses on the teaching and learning of the **design process** when designing in collaboration with other living organisms in an undergraduate context. As stated before, while living materials are an emerging practice, it seems that researchers have been focusing on production, conformation, and manufacturing processes (ATTIAS, DANAI & ABITBOL, 2020). Design **project development dynamics** for the different living materials could be clearer. Attias, Danai, and Abitbol (2020) suggest that

“Prioritizing integrated scientific and design research methodologies can realize new niches, fabrication methods, and applications for mycelium-based materials” (p. 13). As a result, there has been no sufficient attention to the specific demands for development of competencies on the subject. The assumption here is that dealing with this late subject requires a different approach from conventional classroom practices.

In summary, to prepare young designers to contribute to design with the living is clearly a relevant topic that constitutes a knowledge. Considering specifically the teaching and learning scenario it seems biodesign unfolds many implications in the design process that could be clarified. Furthermore, the presented problematic indicates the need to develop “new designerly sensibilities”, new competencies that lie especially in the intersection between Design and Biology. In addition, designers ought to address challenges like user acceptance, applications, and scalability. Under such context, the **research question** tacked on this thesis is framed as**: How to facilitate teaching and learning the DwL (Design with the Living) process in an undergraduate education context with limited resources?**

1.4 AIM AND OBJECTIVES

Considering the research question, the aim of this thesis is to: **To develop and evaluate an artifact for facilitating teaching and learning the DwL process (even) in a limited resource undergraduate education context.** To achieve the aim it is broken down into 5 specific objectives.

1.4.1 Specific objectives

The specific objectives consist of:

O1- To identify artifacts related to the representation and description of the biodesign process and biodesign teaching and learning;

O2- To underline didactic biodesign process models based on interviews with experienced biodesign professionals;

O3 – To define the requirements for a facilitating artifact aiming at biodesign teaching and learning;

O4- To formulate the framework for teaching and learning structure and elements;

O5- To establish an evaluation rubric for the proposed framework and its outcomes;

Following this, an overview of the research methodological strategy is presented which intends to address these objectives.

1.5 RESEARCH SCOPE AND LIMITATIONS

The **research scope** comprises an artifact to facilitate teaching and learning the biodesign process. One key step to develop this artifact is to achieve an in-depth view of the biodesign process. The target audience would be the biodesign community, especially educators and students in undergraduate Design education. The research development context, as mentioned before, is a product design undergraduate program, with no laboratory and limited resources for developing experimentation. This scope was chosen due to its relevance (see justification) and the researcher`s context as a young professor at the Federal University of Paraná`s Design Department.

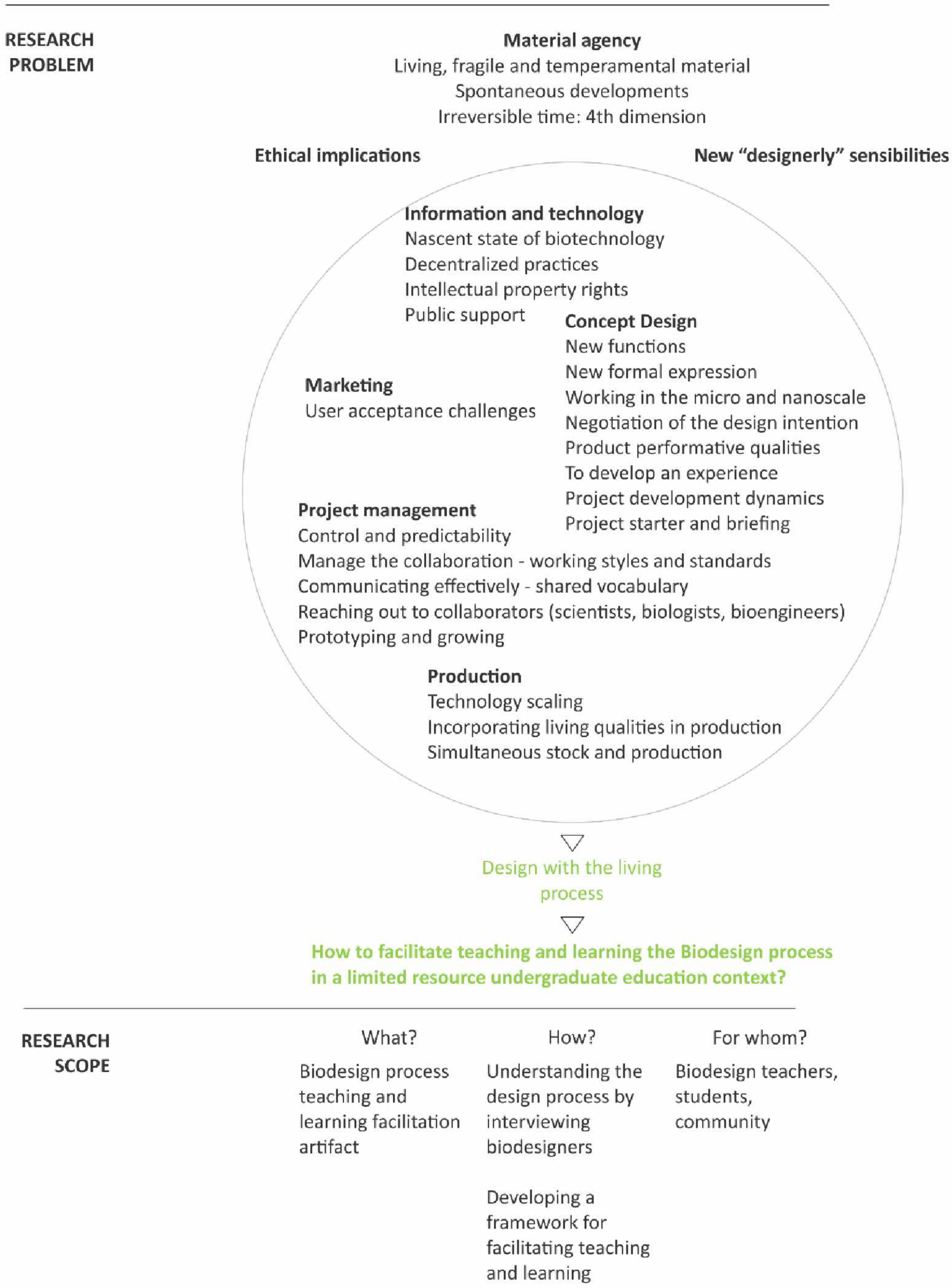
As explained, biodesign seems to be heading toward solid self-organization and formalization. However, **the different names that initiatives assume** make it difficult to try to cover every new development. This is why it is admittedly reported here as a research limitation: that something might escape, despite all the efforts in following events, news, labs, researchers, and systematically and narratively reviewing the literature. In addition, the biodesign process and practice might change rapidly as technology achieves maturity.

Sustainability aspects are widely studied along with design in collaboration with other living organisms. Although sustainability concerns are acknowledged in some parts of this work, it is a research topic of its own, and addressing it would open the research scope in an unmanageable manner.

Other issues are the constraints imposed by the **COVID-19 pandemic**, as well as the time constraints to meet the doctoral schedule. The **time constraint** restricts the number of interviewees and also restricts testing the framework at the Federal University of Paraná – which is the home institution of this researcher.

Figure 3 organizes the key issues and the research scope.

Figure 3 – Research problem and Research scope



Source: Illustrated by the author (2021) based on the literature review.

1.6 JUSTIFICATION

To contextualize the research and the problem, evidence that points out the prominence of biodesign in the design practice was presented. This section describes the study's pertinence regarding its social, academic, economic, and technological relevance. It also elaborates on the research's originality.

The International Convention on Biological Diversity (CBD) opens the Brazilian profile section by stating "**Brazil is the most biologically diverse country in the world**" (2021). Zappi writes on The Kew Royal Botanic Gardens page: "Brazil has over 46,000 species of plants, algae, and fungi, with a higher number of plant species registered than any other country in the world" (2015). The UN Environment Programme (UNEP) emphasizes that with this biodiversity richness "**comes huge potential to boost economic growth and social inclusion, but also a huge responsibility"** (2019). Despite the huge number of species already registered, researchers reportedly find new ones constantly – approximately 700 new animal species are discovered in Brazil every year (UNEP, 2019; CBD, 2021). Concerning the research's **social relevance, it seems appropriate for Brazil to develop protagonism in biodesign for its symbolic and its representative role in global biodiversity**. This initiative seems aligned with the United Nations Sustainable Development Goal 15 – Life and Land, which aims to "Sustainable manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss" (UN, 2021).

Regarding the **academic** relevance, some possible research topics in biodesign which still seem to require attention are listed in the Research Problem section, like design dynamics and product acceptance. Since the Brazilian biodiversity itself offers a whole research agenda for design with the living, the promotion of academic practice and research in this matter presents great environmental relevance. Recently in the first Latin American Biodesign Workshop[4], the workgroup "Pedagogy - biodesign curricula" emphasized the importance of

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[4]The workshop was held on May 13, 2021. It was organized with the support of the Biodesign Challenge Team and led by professor Giovanna Danies Turano from the Universidad de Los Andes, Colômbia. Available at: <https://www.linkedin.com/feed/update/urn:li:activity:6788832730848272384>. Accessed on May 18, 2021.

developing biodesign teaching and learning methods that could better relate to the Latin American context. This study proposes to begin to address the facilitation of teaching and learning the design in collaboration with other living organisms process in our undergraduate context**.** This seems to be in line with the UN Goal 4 for Sustainable Development - Quality Education (UN, 2021).

From an **economic** and **technological** perspective, our biodiversity means opportunity. Different species may open different possibilities for developing artifacts and, consequently, new local productive arrangements. The Labva laboratory (2020) highlights the local characteristic that biofabrication may assume in growing from **local species and resources**. They associate biofabrication with concepts of local sovereignty, territorial autonomy, ancestral knowledge, and circular economies (LABVA, 2020). Besides, special materials and artifacts could be regionally specific, developing unique particularities, similar to what happens in the wine industry. As an example, the Brazilian project "Design da Terra" proposes a model involving the local community in the production of furniture grown from regional Amazon rainforest species (DAMASCENO et al., 2019). They shape the trees into furniture through molds, using traditional grafting and budding techniques, following the aforementioned Fullgrown example. The project intends to benefit the local economy, collaboratively gathering forest, university, and community. **The facilitation of the biodesign process of teaching and learning, and consequently the promotion of its academic practice and research, could contribute to its diffusion, as well as to the maturing of the related technologies and applications.** This seems to meet the UN Sustainable Development Goal 8 – Decent Work and Economic Growth: Sustainablee economic growth will require societies to create the conditions that allow people to have quality jobs"; and also Goal 12 – Responsible Consumption and Production (UN, 2021).

Still from an economic perspective, it appears that designers working with living materials tend to venture into starting their own businesses. This is the case for Modern Synthesis, co-founded by Jen Keane (MODERN SYNTHESIS, 2020); Mogu, co-founded by Maurizio Montalti (MOGU, 2021); and Fullgrown, co-founded by Alice and Gary Munro (FULLGROWN, 2021), to name a few. **Entrepreneurship** is a desirable quality for the Brazilian context and is widely promoted by the Brazilian micro and small business support service, the SEBRAE Agency (SEBRAE, 2021). The agency has 700 centers throughout the country and estimates 52% of Brazilian employment comes from small businesses. Promoting Design with the Living academic practice and research might encourage entrepreneurship and innovative job initiatives focused around the environmental dimension of sustainability.

Finally, **it is important to shed light on the design process with other living organisms itself**. This is key to facilitating the teaching and learning process. The Design Council advocates that there might be a "correlation between business success importance and the importance of a formalized design process" (DESIGN COUNCIL, 2007, p.14). Benefits of modeling the design process and developing an awareness of how it takes place would be: the prospect "**for businesses and investors to identify possible areas for improvement more clearly"; and better management of change and the accommodation of "unexpected challenges**" (DESIGN COUNCIL, 2007, p.14). On this regard, Camere and Karana (2018) have investigated the biodesign process, intervieweing eight designers who worked with living materials. The research focused on detailing the perception and general professional profile and its outcome do not present a model of for the biodesign process.

Hence, it seems there is a **research gap** referring to facilitating artifacts for teaching and learning the biodesign process in an undergraduate education context. This research gap is identified based on a systematic and narrative literature review, which is reported in detail later in this document - and the active participation of the researcher in the most recent biodesign events. These events bring together researchers from around the world, such as the Design with the Living Symposium (DESIGN MUSEUM, 2020); the Biodesign Online Symposium (HBBE, 2020) co-organized by the Biodesign Challenge (BDC), and the Hub for Biotechnology in the Built Environment (HBBE); the launch and the first workshop of the Latin American BioDesign Hub (BDC, 2021a); 'Designing with and for living systems', from the "Teach, Inspire, Create 2021" annual Program of the University of the Arts London (UAL AWARDING BODY, 2021). Turano et al. (2020) developed a facilitating method to teach biodesign in high schools, "Biodiseño en Colegios". Biodiseño en Colegios might have important insights to facilitate teaching and learning in an undergraduate context, but the sense of biodesign it works in is more relatable to biomimicry than to the definition established here. The Material Driven Design (MDD) method has been reportedly used in academic research for DwL, including in undergraduate teaching and learning contexts (PARISI, ROGNOLI; AYALA-GARCIA, 2016; MONNA, 2017; CAMERE; KARANA, 2018; KARANA et al., 2018, COHEN, SICHER; YAVUZ, 2019; GOUGH et al., 2020). MDD is indeed used in facilitating the teaching and learning process with living materials, however, it does not take into consideration important concepts and ethical implications in design in collaboration with other living organisms. Furthermore, DIY and "material design" practices might contribute to the subject, but it must be highlighted that these focus on the material and not always on the concept development (PARISI; ROGNOLI; SONNEVELD; 2017; DIY MATERIALS, 2021; MATERIAL DESIGNERS, 2021).

Therefore, the **originality** of the present study lies in trying to address the gaps in facilitating the teaching and learning the biodesign process, based on a framework that takes into account existing biodesign methods, concepts, reflections, and propositions, and also the practice of professionals. This originality quality might be supported by the **contextual implications** of a limited resources undergraduate program in Brazil.

1.7 METHODOLOGICAL STRATEGY OVERVIEW

To develop a facilitation artifact, this study draws on the Design Science Research (DSR) methodological strategy described by Dresch, Lacerda, and Antunes Jr. (2015). This approach has 12 phases that were clustered and organized in an adaptation according to the specific objectives. This adaptation is detailed in session "3.1 Design Science Research".

Phase "1. Problem and Context" correspond to phases 1, 2, and 3 in the original DSR proposition by Dresch Lacerda and Antunes Jr. (2015) – they concern the problem identification and awareness, which are supported by narrative and literature reviews, as well as the attendance in related events, such as the ones mentioned in the Justification section. The main outcome of this phase is the identification of a research gap. The main outcomes here are the concepts and terminology in the biodesign practice and research context.

Phase "2. Related Artifacts" concerns the Identification of artifacts and classes of problems. The literature review is still an important methodological procedure at this point, as well as the in-depth interviews with designers working in collaboration with living organisms. The Double Diamond framework from the Design Council (2007a; 2007b), Rosenfed et al.'s (20006) Product Development Process (PDP), and the Mosaic Method (KIM; LEE, 2015) are used to organize the data obtained in the literature review and the interviews.

With this data, **models** of the biodesign process are underlined. These models are considered supporting artifacts.

Phase “3. Development” relates to the design and development of the facilitation artifact for teaching and learning the biodesign process, which is a **framework**. Along with it, an evaluation rubric to aid the instantiation in the next phase is developed.

In Phase “4. Evaluation” the artifact is evaluated. This means the **instantiation** of the framework. For this phase, the application of the framework happened in UFPR’s mandatory course Materials and Processes III in the Product Design undergraduate program. The analysis is made by triangulation. A fourth evaluation step is added at the end: insights from an immersion at the Cluster of Excellence Matters of Activity at the Humboldt University in Berlin. One important outcome in phase 4 is the framework’s contingency heuristics.

Phase “5. Conclusion” refers to the clarification of achieved learnings, conclusions, and the generalization for a class of problems. In this phase, the possibilities to generalize the contingency heuristics for a class of problems are discussed.

Finally, the communication of the results is presented in the Appendix, which happens mainly through publications in papers and conferences.

1.8 THESIS STRUCTURE OVERVIEW

The thesis structure follows the PPGDesign regulations rigor.

Chapter 1 introduces the research, outlining the Design with the Living context, presenting the research problem, its scope, and limitations, as well as elaborating on the research relevance, originality, and viability.

Chapter 2 refers to the **theoretical background** of the thesis. It describes important concepts and contexts brought in the literature review. Here ethical implications are overviewed, as well as the biodesign practice, and biodesign teaching and learning practice.

Chapter 3 details the **methodological strategy** and procedures.

Chapter 4 shows the **results**. It includes the analysis of existing artifacts and the biodesign process models; the development of the facilitation framework artifact; as well as the evaluation rubric for the framework and its outcomes. In this chapter, the framework is also evaluated.

Chapter 5 **discusses** the outcomes and results.

In Chapter 6 **final considerations** are drawn.

The Appendix presents additional documentation, such as questionnaires, local ethics committee approval, and publications that resulted from this study, communicating the results. Proceeding to chapter 2, the research's theoretical background is detailed.

2 DESIGN WITH THE LIVING CONCEPTS AND PRACTICE

This chapter is dedicated to expanding and characterizing concepts and definitions of Design with the Living, laying the **theoretical framework** for the study. Figure 4 offers the chapter overview. This is a compilation of selected themes and discussions that are emphasized in the systematic and narrative literature review. It begins with concepts and definitions; followed by the discussion of ethical implications; then biodesign artifacts are characterized as well as the state of their current applications; next, the biodesign practice and models which organize it are introduced; and finally, an overview of biodesign teaching and learning is provided.

Figure 4 – Theoretical background chapter overview

Chapter overview

1. Introduction	2. Design with the living concepts, and practice	3. Methodological strategy and procedures	4. Lessons on the biodesign process	5. Discussion	6. Conclusion	Appendix

2.1 Design with the living concepts
2.2 Ethical implications
2.3 Characteristics of biodesigned artifacts and materials
2.4 Introduction to the biodesign practice and organization
2.5 Design process in collaboration with other living organisms
  2.5.1 A change in the designer's role
  2.5.2 Collaborative iinternational practices and open-source resources
  2.5.3 Design negotiations
  2.5.4 Thinking systems
  2.5.5 Design process control
  2.5.6 Design representation
  2.5.7 A new vocabulary to the language of form
  2.5.8 A fourth dimension: time
  2.5.9 New possibilities in making
  2.5.10 The design process with the living phases
2.6 Teaching and learning Design with the Living
  2.6.1 Formal education
  2.6.2 »Matters of Activity. Image, Space, Material«
  2.6.3 LabStudio
  2.6.4 Biodesign Challenge

Source: Illustrated by the author (2023)

2.1 DESIGN WITH THE LIVING CONCEPTS

As described in the introduction, it seems there is not a consensus on the terminology when describing the design activity with living organisms. While the term **"living material" is used by authors that keep the organisms alive in the artifacts, others "deactivate" them after production**, usually the case with fungi (CAMERE; KARANA, 2017; 2018; ATTIAS et al., 2019). Algae, for instance, is argued by Camere and Karana (2018) as an example of "**Growing design**" (explained later in this thesis), a living material, even in the cases they are harvested and processed to extract cellulose or agar-agar to form biopolymers. However, this process would resemble material production cycles that are not considered living materials, such as the case of cotton, which is harvested and processed to produce textile fibers (STROBEL; HEEMANN, 2020).

Dade-Robertson, the editor of the Bio Design book series by Routledge, categorizes the living in what would be: (1) "life-like and does not necessarily involve biology", such as the aforementioned responsive materials; what would be (2) "life-like but pre-biotic", such as technologies including protocells; and (3) "artificial life" created by computers, imitating growth, self-replication, responsiveness to the environment, metabolism and even capability to evolution (DADE-ROBERTSON, 2021, p.6). The author defines for the purpose of his book, life as "**biological cells**", and the term "**biological system**" to refer to either single or multi-celled organisms. **In this thesis, biodesign is meant as Dade-Robertson describes it: "[...] design and design research which use living systems as part of their production and operation"** (2021, series introduction note).

Finally, the design approaches developed by researchers, designers, and artists branched into new terminology and concepts, these concepts are addressed later in this chapter.

2.2 ETHICAL IMPLICATIONS

Antonelli observes that "Design transcends its traditional boundaries and aims straight at the core of the moral sphere, **toying with our most deep-seated beliefs**" (2018, p.7).

When working with other living organisms to build artifacts, many **ontological and axiological** issues are raised regarding an **anthropocentric view of the world** (MELKOZERNOV; SORENSEN, 2020). Melkozernov and Sorensen (2020) express a transition is needed for **biocentric and ecocentric understandings of life**. Mancuso (2019), for example, remarks that because plants evolved with different strategies than those of animals, they do not have a face or similar recognizable structures. He says we do not understand these living beings and consequently treat them just like part of the landscape, therefore they would be invisible and a **resource to be used**. Grushkin observes “There’s a general appreciation for the Gaia theory of James Lovelock and Lynn Margulis, where all life has evolved as a singular planetary whole; this gives the biodesign field a different view of what it means to be human” (2021).

Pataranutaporn, Ingalls, and Finn (2018) describe how DNA is being rewritten for bio-computation, to store and even process information. The authors argue that new technological frameworks need to be developed to describe and design the interface between biological systems and digital systems, which would imply **opening the boundaries between the living and non-living matter**. This movement would raise “ethical questions around exploitation and bioethics" (PATARANUTAPORN; INGALLS; FINN, 2018, p.5). Synthetic biology would change our perception about the living, breaking life into functional assembly blocks, and allowing one to build something alive on demand (VETTIER, 2019). Kera (2014) argues that **synthetic biology can create new organisms and increase nature’s complexity**.

Vettier (2019) discusses ethical aspects of several biodesign projects. The author asks: “**To what extent is it acceptable to replace mechanical and industrial systems with biological processes? Who controls the living matter? Does it need to be controlled**?” (VETTIER, 2019, p.28). Vettier questions the use, purpose, ecosystem, and lifecycle of the living object and also **“who decides the end of the object’s life?”** (2019, p.28). She continues to discuss what it means to be alive, citing Tristan Garcia’s definition: **a living organism spends energy to defend the difference between being and not being**. Rhythm, transformation, change, regeneration, and interaction through time would be inherent to the indicators that something is alive (VETTIER, 2019). Ginsberg et al. ask “How are we to manage the ownership of life’s material?” (2014, p.xi).

Ethical issues are also being discussed in online communities for designing with living materials that are emerging, open forums and hackerspaces that promote international challenges, and also arise from open source technology made available (KERA, 2014; DAMSIN, 2019; VETTIER, 2019). These initiatives often imply synthetic biology practices as well, such as genetic modification in organisms. In the communities, research and discussion happen collaboratively and horizontally, joined by artists, universities, independent researchers, designers, and engineers. Ethically, there is a concern presented by Kera (2014) about this experimental collaborative process to build protocols, which could lead to what the author cites as "**scientific self-regulation**" or "**scientist-centric ethics**" and "**models of justification**". Those terms presumably imply deregulation, the demise of governance, and could be prone to commercial pressure (KERA, 2014). On the other hand, the author considers this setting an opportunity to encourage interactions between codes, norms, and protocols with **public participation in science**, along with other benefits, such as network formation and **knowledge transferring** (KERA, 2014).

Myers warns:

> Designers and architects are still people bound to their cultural biases and personal frailties. Aspects of inherited, dysfunctional impulses, such as neo-colonialism, a rush to change for its own sake, myopic pursuit of profit, and media-savvy theatricality out of proportion with practical potential, will persist as design develops new intersections with the life sciences (MYERS, 2018, pp. 16-17).

Collet (2020) advocates each design approach to nature will have its own ethical implications. In her framework, presented later in this document, "Nature as a Model" would **recognize the mastery** "of solutions that have evolved over 3.8 billion years and their ecological advantage" (COLLET, 2020, p.5). "Co-working with Nature" would have embedded values of "**cooperation and partnership**". In contrast, "Nature as a hackable system" would imply "values **of control and dominance** inherent to the twentieth-century idea of Nature as an **exploitable limitless commodity**" (COLLET, 2020, p.5).

In discussing Bio-art in the XXI century, Melkozernov and Sorensen (2020) present the critique it brings forward to anthropocentric values. According to them, public opinion about **synthetic biology is negative and bio-artists could contribute to, at least, a better understanding by the public of what this technology could mean and express**. The authors state that this technological approximation and understanding brought by Bio-art transforms our society by "testing the biological limits of humans as species" (MELKOZERNOV; SORENSEN, 2020, p.5).

Another ethical concern is the **intellectual property** of life and processes with living organisms. Ginsberg et al. question "How are we to manage the ownership of life's materials?" (2014, p. xi). Attias, Danai, and Abitbol (2020) reviewed the literature analyzing industrial design and architecture applications, they found that most of the scientific literature does not detail species and productive processes in a reproducible manner due to commercial protection patenting issues. Collet (2017) and Zhou et al. (2020) explicitly state patent registration in their works.

In "Living Construction", Dade-Robertson writes a note on "Ethics and society" explicitly committing to only publish works that observe their established ethical position. This means: not publishing research directly applicable to the development of weapons; making risks clear when processes and experiments might be harmful to the individuals conducting them or the environment; and authors are required to confirm that "appropriate risk assessment, ethics review, informed consent and animal welfare protocols have been met, in compliance with local institutional and governmental regulations" (DADE-ROBERTSON, 2021, Ethics and society).

Ultimately, ethical implications branch from the way we as humans see other living beings and the environment, how we relate to them; passing by policies and regulation issues; and the ownership of knowledge and life itself.

2.3 CHARACTERISTICS OF BIODESIGNED ARTIFACTS AND MATERIALS

To provide an overview of the biodesign artifact and material characteristics, what was retrieved from the literature review on this matter is summarized. Most studies refer to the living material characteristics and not to the final designed products, but the current mentioned applications are organized along with the species involved.

As stated previously, the living quality of the material seems not to be consensual among researchers. Liu et al. (2017) detail that to keep the organisms alive embedded in the material, **the artifact 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 without the artifact itself. The main concern in these cases is **maintenance**, which comes across with similar concerns bio art faces, as expressed by Brayer (2019), Bianchini, and Quinz (2019). Many hydrogels and elastomers which might be infiltrated with nutrients are being developed and tested to create these necessary conditions (LIU et al., 2017). Structures are also being studied, such as optimal shapes, cavities, and sizes to accommodate the organisms into the artifacts, 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 endeavor 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*.

Another approach is to maintain the organism in a **"deactivated" or dormant state** after the object is considered finished, this is the case in bacterial cellulose and mycelium-based materials. Zolotovsky (2012) describes in a bacterial cellulose experiment that **a small fraction of the organisms are kept alive** and continue to grow and reproduce when the nutrition and growing conditions are available again. The authors observed "**self-healing**" in their experiment (a tear on the bacterial cellulose was mended by the bacteria) and see this as an opportunity to experiment with the organism's response to stimuli (ZOLOTOVSKY, 2012). Mycelium is also deactivated after the artifact reaches its final shape. Blast Studio (2020) reports developing modules of 3D columns, which are mended by the further growth of the fungi.

The **aesthetic and experiential qualities** of living materials are reportedly different from the consumers' usual repertoire, this 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). People would not be used to domestic products that would **change with seasons** (KEUNE, 2017). Keune advocates that living materials invite a reflection on the **cultural and aesthetic bias toward natural processes in interior scenarios**, what they call the "diachronic properties of the materials". Instead of fixed properties, there would be a rather momentary stabilization of the material qualities and a performative view of materials. Karana et al. (2018) advise that those unique **experiential qualities must guide the design with living materials**. Companies that market mycelium products, for instance, are reportedly strategically adding value by arguing (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). Ayala-Garcia and Rognoli (2017) discuss aesthetics and descriptors for living materials that fit in 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 incorporate the special characteristics related to each **organism's abilities.** Some examples are mentioned in the literature, for instance, some bacteria species might produce 100% pure cellulose, which is not the case for plant and animal-based cellulose (CAMERE; KARANA, 2018). Other examples are the fungi species that are being studied for their resistance to radiation (SHUNK; GOMEZ; AVERESCH, 2020); and bioluminescent bacteria (KERA, 2014).

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 be **archetypal objects**, such as lampshades, chairs, and flower vases. Their purpose is to make the material understandable through a simple known artifact (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**. Biodesign objects are often viewed as a **sustainable alternative** to traditional materials, such as petroleum-based polymers (CAMERE; KARANA; 2018 ATTIAS et al., 2019; ANTINORI et al., 2020). Camere and Karana (2017; 2018) outline some hypotheses on the demonstrator and surrogate applications, such as lack of time for designers, which would focus strictly on technical issues, or prefer to manage functional expectations, hence introducing demonstrator products to present a new sustainable material (KARANA et al., 2018). **They 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.

While the commercial application of living materials still faces some challegnes, Dade-Robertson (2021) highlights the "Technology Readiness Level" (TLR) [5]of biodesign for now. According to him, TLR was initially developed to grade NASA R&D projects for mission readiness: "We need to recognize that our research may reside for some time at TRL levels 1, 2, or 3. Our collaboration with the living is one in which we are only just beginning to understand the language of our collaborators" (DADE-ROBERTSON, 2021, p.9).

Table 1 presents the distribution of applications per species found in the systematic literature review sample. The procedure to review the literature is described in chapter 3.

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[5] The Technology Readiness Level chart has 9 Levels, which Dade-Robertson (2021, p.8) describes:

1- Basic principles observed and reported;
2- Technology concept and/or application formulated;
3- Critical function, proof of concept established;
4- Lab testing of prototype component or process;
5- Laboratory testing of integrated system;
6- Prototype system verified;
7- Integrated pilot system demonstrated;
8- System complete and qualified;
9- System proven in an operational environment

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 Karana (2017)	Fungi, bacteria, plants, algae	-
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;

Table continues next page

Table 1 – Application distribution according to authors

	Publication	Life form	Applications
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;
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

Table continues next page

Table 1 – Application distribution according to authors

	Publication	Life form	Applications
			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-Kristensen (2020)	Biological materials	Circumventive organs, bio-encryption, lung-on-a-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

Table continues next page

Table 1 – Application distribution according to authors

	Publication	Life form	Applications
			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)

Other applications may be found outside the scientific literature and might complement this compilation.

2.4 INTRODUCTION TO THE BIODESIGN ORGANIZATION

According to the Design Council's literature review, from a historical perspective, the **scope of design would have "broadened to include disciplines** such as interaction, experience, and service design" (DESIGN COUNCIL, 2007b, p. 12). Additionally, it also addresses the company's organizational structure, marketing and branding, being the uniting element of engineering, sales, marketing, and manufacturing. **The intersection with biology seems to reportedly bring other dynamics to the design process**.

"Biodesign: Nature, Science, Creativity" is a notable reference in biodesign (MYERS, 2018) – it contains curated works organized in the chapter structure:

a) **The Architectural Hybrid - Living Structures and New Ecological Integrations:** In this approach, designers and architects embrace the complexity and uncertainty of the unbuilt environment, giving up "full control", exploiting "advances in biology, including synthetic biology, to build more ecologically". As a result, creations in this chapter are "hybrids of animate and inanimate material" (MYERS, 2018, pp. 20-21);
b) **Ecological Object Engineering - Replacing Industrial and Mechanical Processes:** This category considers design on a human scale, smaller than architectural projects. It focuses on how biologic, natural, or engineered, processes "are being considered as viable alternatives to those of more conventional technologies. [...]" (MYERS, 2018, pp. 78-79);
c) **Experimental Functions - Speculative Objects, Teaching Tools and Provocations:** Examples Myers organizes in this category "hack life into new machines". The author gives a great emphasis on experimentation in design and the continuous evaluation of the expansion of what is possible, even if improbable. The category "Introduces cautionary tales, critical commentary, and experimental technologies meant to spark discussion about potential –

and often surprising – future functions of design" (MYERS, 2018, pp. 138-139). He presents projects that explore the intersection of a diverse set disciplines, synthetic biology, and the do-it-yourself biology (DIY bio) movement;

d) **Dynamic Beauty - Artwork Crawling off the Auction Block**: here Myers introduces works that intersect with biology and express beauty and aesthetic explorations without the need to establish a function - "creating original aesthetic experiences and laying the foundation for a new conception of beauty" (MYERS, 2018, p. 204).

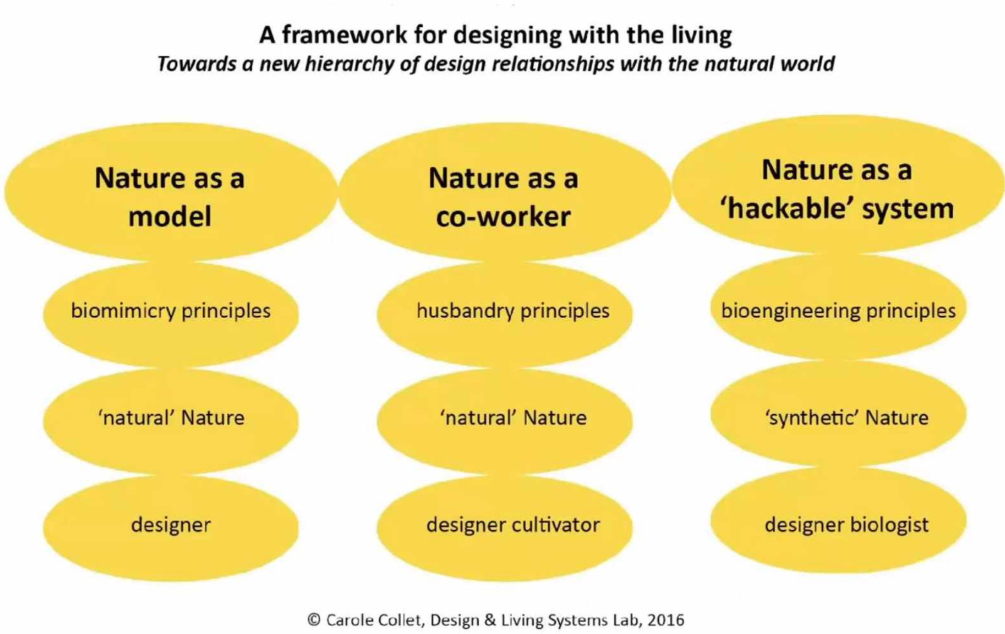
Another seminal organization of biodesign categories is the 2013 exhibition "Alive: New Design Frontiers", which took place in Paris and focused on the **role of designers in the biodesign scenario**. They were organized by the exhibition's curator, Collet[6] (2013; 2017; 2020), and unfold as follows:

a) "**Plagiarists**": where designers would take nature as a model, applying **biomimicry principles to imitate processes or behaviors** with man-made and digital technologies;
b) "**The new artisans**": here designers **consider nature as a co-worker, as a collaboration process**. In this scenario, design would be comparable to gardening and farming, instead of manufacturing;
c) "**Bio-hackers":** in this category, designers would **reprogram a "synthetic" nature**. It would involve extreme bioengineering, illustrating a possible future;
d) "**New Alchemists**": where designers would **create new hybrid organisms**, combining living with non-living, what Collet (2013a) calls a hybridized nature;
e) "**Agents Provocateurs**": in this approach, designers would **conceptualize and imagine nature**. They could propose a provocative far future, debate ethical issues in living technology, and in what Collet (2013) refers to as high-tech sustainability.

[6] Carole Collet is a Professor in Design for Sustainable Futures at Central Saint Martins, University of the Arts London, and director of the Design&Living Systems Lab (COLLET, 2021).

The same author also released a framework to organize biodesign (Figure 5) based on the **designer-nature relationship types** she envisions, where the designer roles are summarized in three hierarchical folds. Collet (2017) considers these as essential to developing a "critical stance" to lead to ethical discussions.

Figure 5 – Collet's Framework



Source: Collet (2020, p.4)

The three folds in biodesign

Camere and Karana (2017; 2018) also propose a framework to organize approaches to designing with nature. Collet (2013) was their starting point, but the authors also mapped other initiatives from exhibitions and references. Their framework is represented in Figure 6, with examples provided by the authors, and unrolls in the following categories:

a) **Augmented Biology**: in this approach, designers would seek to have a more predictable nature, with faster and repeatable results. Synthetic biology is employed to redesign nature seeking to solve challenges such as famine;
b) **Digital Biofabrication**: the main characteristic of this approach is the use of advanced computational tools to 'hack' biological systems to open up possibilities. This approach might also take advantage of synthetic biology but

does not rely solely on it. New "material ecologies" are formed, hybrid from natural and artificial, modeling how organisms will behave through computational tools;

c) **Biodesign Fiction**: brings highly conceptual visions grounded in speculative design. Designers debate the implications of biotechnological futures (CAMERE; KARANA, 2018);

d) **Growing Design**: it is considered a more artisanal approach, characterized by the authors as cooperation with nature to achieve specific design purposes. The fabrication process is rooted in crafting, and the genetic structure of the living organisms should not be altered. Designers actively engage in growing and developing materials. In this logic, Growing Design would also include DIY materials. The material is envisioned to be used in products for the present or a probable future and not for speculative scenarios. Designers who work growing materials often compare it to traditional practices, such as making bread and beer (with yeast), as well as harvesting (CAMERE; KARANA, 2018).

Figure 6 – Camere and Karana's Framework

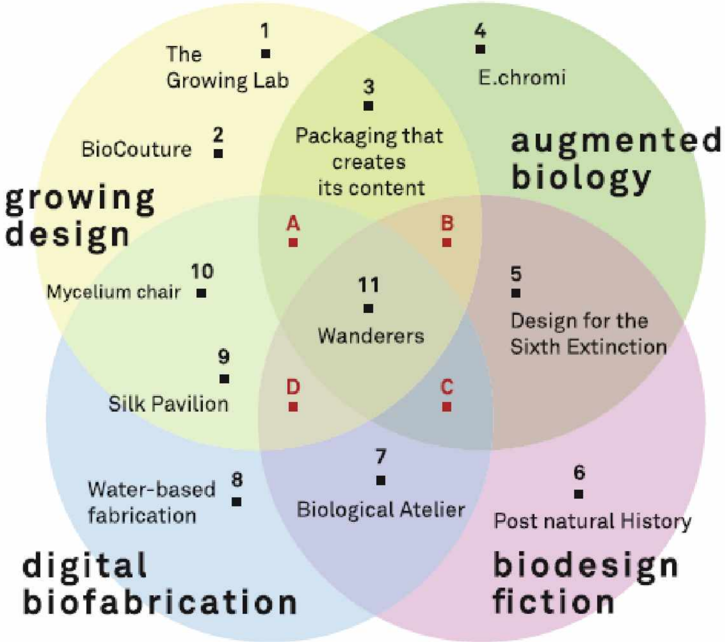


Fig. 2. Four approaches cross-fertilizing design with biology and related cases: 1) materials and product from mycelium (Montalti, 2010);2) a collection of garments from bacterial cellulose (Lee, 2011); 3) a packaging grown by engineered bacteria that also produce its content (Lim & Carey, 2013); 4) self-diagnosis toolkit employing engineered Escherichia coli (Ginsberg, 2009); 5) Engineered organisms to revive ecosystems in speculative future (Ginsberg, 2013); 6) luxury fashion items for 2080 grown by biocells (Congdon, 2013); 7) Speculative encyclopedia of new living species (Fournier, 2012); 8) biomaterials fabricated through additive manufacturing (Mediated Matter MIT Lab, 2014); 9) digitally fabricated structure completed by silkworms (Mediated Matter MIT Lab, 2013); 10) 3D printed chair completed by mycelium (Klarenbeek, 2013); 11) bio-augmented wearables for extreme planetary environments (Oxman, 2014).

SOURCE: Camere and Karana (2017, p. 103, 2018, p.572)

Camere and Karana (2017; 2018) point out that it is very usual for cases to fit in the description of more than one of the approaches and thus stay in the intersections in between these categories.

In "Can we grow a city?" Dade-Robertson (ed., 2021b) and the Hub for Biotechnology in the Built Environment team outline four fabrication strategies, which could be considered as an organizing framework for biodesign as well:

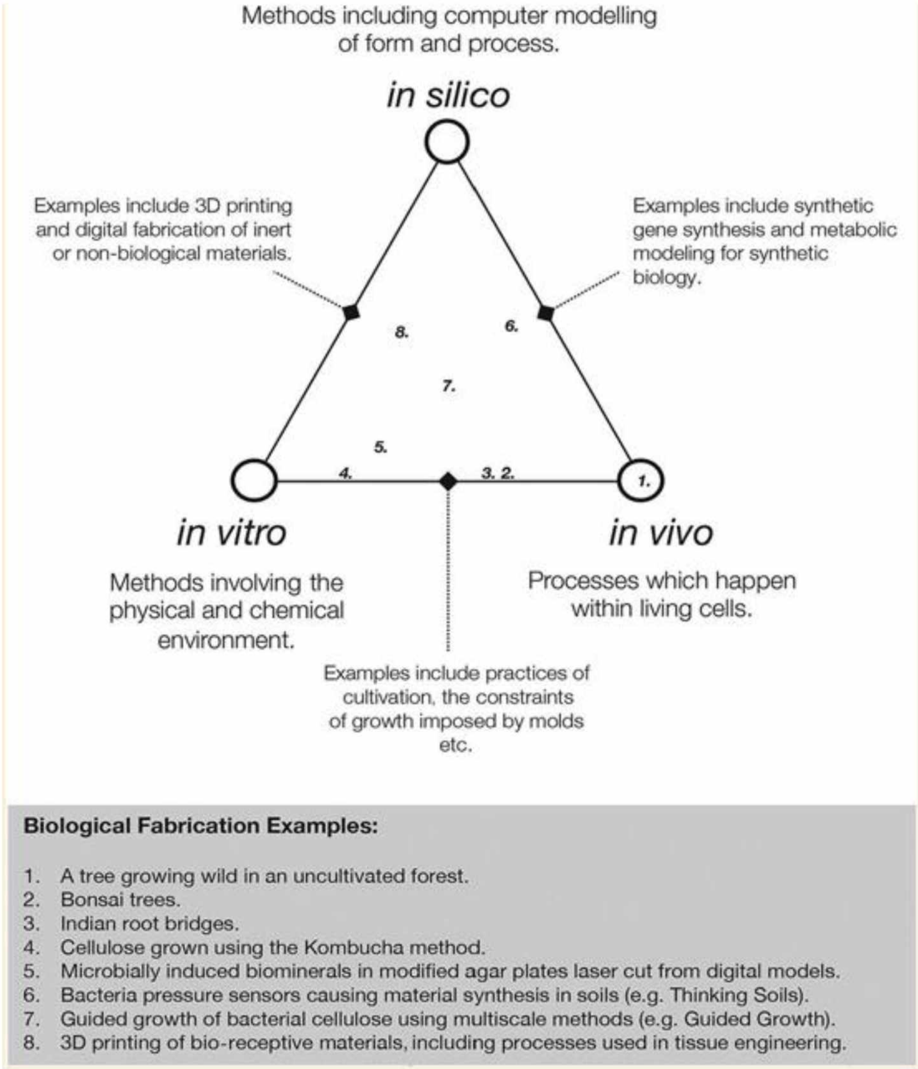
1- **Material made of living cells:** such as mycelium, which acts as a binder for the creation of a composite material;
2- **Materials made by living cells:** such as bacterial cellulose, which is excreted outside the bacteria cell membrane;

3- **Materials which are induced by living cells:** for example, calcite precipitated around certain types of bacteria in response to chemical changes caused by the microbe**;**

4- **Materials that are made active by the inclusion of cells:** the authors give an example of a hygromorphic material that responds to water changing shape, composed of bacterial spores coded on latex.

Dade-Robertson's (2021a) "diagram of domains of information in biological fabrication" (Figure 7), could also be a structure to organize biodesign. The author explains the concepts of (1) ***in vivo;*** which refers to the process that happens in the living cell; (2) ***in vitro,*** which "[...] refers to a broader notion of the human control of the chemical and physical environment" (DADE-ROBERTSON, 2021a, p.62); and (3) ***in silico***, as for computer-mediated processes. The author refers to these concepts as information domains: *in vivo* (information in the cell) *in vitro* (information in the environment), and *in silico* (information held within a computer, altering in vitro parameters) - and fabrication results depend on the interaction of both domains (DADE-ROBERTSON, 2021).

Figure 7 –Dade-Robertson's Information Domains Diagram



Source: Dade Robertson (2021, p. 79)

Top-down and **bottom-up** would be another possibility for organizing the biodesign practice. Dade-Robertson writes about the concepts: "notions of top-down and bottom-up have a range of definitions in design, but, in synthetic biology, bottom-up design is seen in attempts to construct novel artificial life from scratch" (DADE-ROBERTSON, 2021a, p.60) whereas top-down design, explains Dade-Robertson, modifies existing organisms. The author explains that truly bottom-up design is yet in a very early stage: "In reality, therefore, when we discuss bottom-up versus top-down, **we are usually making a reference to the complexity of the organism we are working with and the degree of influence we have in defining the outcome of a fabrication process**" (DADE-ROBERTSON, 2021a, p.61).

Table 2 gives an overview of the different possible frameworks for organizing biodesign.

Table 2 – Overview of Design with the Living (biodesign) organizing frameworks

Myers (2018, first published in 2012)	Collet(2013)	Collet(2016)	Camere and Karana (2017)	Hub for Biotechnology in the Built Environment (Dade-Robertson, 2021b)	Dade-Robertson (2021a)
Architectural Hybrid Living structures and new ecological integrations; architectural scale;	**Plagiarists** Biomimicry principles	**Nature as a model** Biomimicry principles and a “natural” nature (contemplation – nature is above)	**Augmented Biology** Synthetic biology is employed to redesign nature seeking to solve challenges	**Materials made of living cells**	**Bottom-up design** “bottom up design is seen in attempts to construct novel artificial life from scratch” (DADE-ROBERTSON, 2021a, p.60)
Ecological Object Engineering Replacing industrial and mechanical processes; human scale; usability	**The new artisans** Nature as a co-worker	**Nature as a co-worker** Designer as cultivator using husbandry principles and a “natural” nature (working with – nature is side by side)	**Digital Biofabrication** Use of advanced computational tools to ‘hack’ biological systems to open up possibilities	**Materials made by living cells**	**Top-down design** “Modifies existing organisms”
Experimental Functions Speculative objects, teaching tools and provocations, intersection with disciplines; possible but improbable	**Bio-hackers** Reprogram a "synthetic" nature	**Nature as a “hackable” system** Designer as biologist using bioengineering principles and a “synthetic” nature (intervening – nature is under)	**Biodesign Fiction** Debate the implications of biotechnological futures	**Materials which are induced by living cells**	***In Vivo*** Design information in the cell - to better develop the desired material qualities while the material is being formed by the organism: in vivo, or in the living
Dynamic Beauty Artwork; not necessarily a function; discussing aesthetics and meaning	**New Alchemists** Create new hybrid organisms	-	**Growing Design** Cooperation with nature to achieve specific designs; no synthetic biology, more like a craft	**Materials that are made active by the inclusion of living cells**	***In Vitro*** Design information in the environment “refers to a broader notion of the human control of the chemical and physical

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Table 2 – Overview of Design with the Living (biodesign) organizing frameworks

Myers (2018, first published in 2012)	**Collet(2013)**	**Collet(2016)**	**Camere and Karana (2017)**	**Hub for Biotechnology in the Built Environment (Dade-Robertson, 2021b)**	**Dade-Robertson (2021a)**
					environment" (DADE-ROBERTSON, 2021a, p.62)
-	**Agents Provocateurs** Conceptualize and imagine nature	-	-	-	***In Silico*** Design information held within a computer, altering in vitro parameters
Scale, technology "readiness", function to humans	**What do designers do?**	**Relationship and ethical stand**	**Making techniques and technology "readiness"**	**What do organisms do to materials?**	**What is the hierarchical level of intervention? Where is the information?**

Source: Organized by the author (2021) based on Myers (2018), Collet (2013; 2016), Camere and Karana (2017), and the Hub for Biotechnology in the Built Environment (Dade-Robertson, 2021a; 2021b)

Given the existing frameworks that organize biodesign, the next section proceeds to describe the biodesign process practice particularities according to the literature.

2.5 DESIGN WITH THE LIVING PROCESS

In this section characteristics of the biodesign process and practice are summarized as found in the literature review. Some of these characteristics were already introduced in chapter 1, in the research problem section.

Camere and Karana (2018) characterized the **Growing Design** process, one of the variations of biodesign, as follows:

a) It would be **co-performed** with nature, the outcome is mediated by the organism's agency;
b) The **making of the material and the product would be simultaneous**: the material production/extraction does not come before the product is formed;
c) It would be an "intimate" process, "**looking after another living being**", a "visceral bonding";
d) The authors consider Growing Design to be a **bottom-up** process, which, in this context, means a "material-driven approach, starting from understanding the materials" (CAMERE; KARANA, 2018, p. 577);
e) It would be **a structured process**: protocols are developed for experimenting according to the variables and themes;
f) Although structured, it would also be **intuitive** and imply serendipity;

Considering the general biodesign practice, Dew and Rosner (2018) name five characteristics of living materials that would be important to be considered: "**(1) legible textures, (2) defensive traces, (3) reparative expressions, (4) vital decay, and (5) performative scarcity**" (DEW; ROSNER, 2018, p.11). (1) "Legible textures" would mean understanding the **physical patterns the living material provides related to its change**, e.g., the tree rings. Designers ought to pay attention to the patterns, as they might reveal something about the material, its past, and future possibilities. (2) "Defensive traces" would refer to the clues the material provides to its past, and designers would have to "navigate past damage in finite resources" (DEW; ROSNER, 2018, p.4). As for (3) "reparative expression", the authors exemplify the running sap of a tree as a **response to damage**, which could be used in forms and creative expressions. (4) "Vital decay" would refer to **complex non-human influences designers have to consider**, such as "influential forces of gravity, weather and aging" (DEW; ROSNER, 2018, p.5-6). Finally, (5) "performative scarcity" "exposes how **working with damaged material** recognizes resource scarcity as a vital feature of the material at hand" (DEW; ROSNER, 2018, p.6). Based on the difference the diachronic properties of materials could make in a design project, these authors propose three methodological orientations:

a) "**Designing for material recuperation**", which would imply a rehabilitative design process;
b) "**Collaborating with more-than-human actors & timescales**", which envisions a post-anthropocentric making, considering more than human values and encounters, where forces of decay would act as co-designers;
c) "**Approaching material properties as prototyping sites**", in which prototyping would denote "temporary alignments between material and meaning, explorations into what the properties might be for now and in this assemblage" (DEW; ROSNER, 2018, p.9). This approach emphasizes an openness to reworking instead of universal and permanent properties.

Besides Camere and Karana's (2018) characterizations and Dew and Rosner's methodological orientations, the biodesign process is not often fully described in the literature that concerns biodesign. The information retrieved in this matter is summarized in the next sections by topics:

2.5.1 A change in the designer's role

One common ground found among authors in biodesign is the change in the role and practice of design (OXMAN, 2015; BERNABEI; POWER, 2016; COLLET, 2017; CAMERE; KARANA, 2017; 2018; DEW; ROSNER, 2018; COLLET, 2020). The designer's role would expand **from form-giving to growing and developing new materials**. Camere and Karana (2018) conclude: "Growing Designers forge the conditions for invention of new matter, which could not exist otherwise" (CAMERE; KARANA, 2017, p.111). Camere and Karana (2018) and Karana et al. (2018) concluded that most designers that work with living materials focus on the production process. Besides the impact of the living qualities of the organisms in the design process, there seems also to be a change of attitude of the designer toward the designed artifact. Camere and Karana found that designers change how they **perceive their relationship** with the artifact when working with living materials: "**you have a sense of death**", as one of their interviewees stated (2018, p. 576). The authors also described **changes in consolidated design activities. Prototyping,** for instance, would be part of the form-giving process already in the beginning and would require experimentation with the organism's growth. Form-giving and plastic research could be only programmed and defined to the limits given and **mediated** by the living organism.

2.5.2 Collaborative international practice and open-source resources

If the role of designers changes when biodesigning, it is not only designers that have been doing it. Kera (2014), Damsin, (2019), and Vettier (2019) describe designing with other living organisms as a very experimental **collaborative practice on a global scale** among independent and associated designers, artists, architects, makers, biologists, researchers, scientists, companies, and universities. Online communities **share knowledge and open-source** resources and collaborate on developing protocols, tools, and ethical discussions (KERA, 2014). An example of the diverse and collaborative creator's scenario working with living materials is presented in exhibitions like "La Fabrique du Vivant", in 2019 in Centre Pompidou, Paris. The exhibition showcases the approximation of this creator community to propose an "archeology" of the living and the artificial life in artistic creations (BRAYER; ZEITOUN, 2019).

From the book Biodesign – Nature, Science, Creativity (MYERS, 2018), some advice for collaborating from Myers himself and Cho (2018) is extracted. In the "Frequently Asked Questions" chapter, Myers answers the question "Are there non-scientific routes for biodesign?" (2018, p. 269). He advises that traditional craft practices might turn into biodesign projects, such as agriculture, brewing, baking, and gardening - and those might be easier to approach. **Although these are science-based approaches, they do not necessarily require collaboration with a scientist because the information would be available from "large amateur communities devoted to these activities"** (MYERS, 2018, p. 269).

However, in biodesign, designers will probably, at some point in their careers, collaborate with scientists and biologists. According to Cho (2018), this might be a delicate endeavor, and he offers some advice for getting started. In the outreach, one must **(1) find the right institution or expert** when more than one contact must be made to develop collaboration, and **(2) build a previous understanding of the science** he or she wishes to get involved. This should be done "through scientific research papers [...] to move a project forward and establish its legitimacy" (2018, p.266). However, Cho warns to be careful with sensationalized media. He refers to the development of "**scientific literacy**" and advises that the designers should look for the names of relevant scientists and read about techniques and papers related to the topic. Not every technical scientific aspect must be understood, but enough to provide insight and "substantive exchange" in the designer-scientist collaboration. The proper lexicon allows scientists to be specific about their work. Designers must be familiarized with specific descriptions of the biological process or mechanism of a biological technology: "you must be able to describe these processes on your own, employing the same terminology" (CHO, 2018, p.267). Cho continues to advise designers to (**3) understand the individual and their work** in order to show and propose links and mutual benefits to their research and the goals of a possible biodesign project. According to Cho (2018), a good reach-out script would be to: "a) Write a clear description of why you're reaching out to them and any affiliation you have, e.g., university; b) Include details that demonstrate you have read at least one of their academic papers; and c) Explain how working together would be beneficial for both parties" (CHO, 2018, p.267). When contacting a scientist, lab, or company, designers must also discuss **(4) authorship, crediting, and ownership as soon as possible**: "[...] be aware, as scientists work for universities and private labs, that these places may have their own rules for intellectual property (IP). [...] Mutual benefit should be a goal – think about what you as a designer can bring to the scientist" (CHO, 2018, p.267). Finally, Cho recommends building a good relationship: **(5) crediting, thanking, and keeping in touch with collaborators, making sure they are aware of the acknowledgments.**

2.5.3 Design negotiations

It is not only with scientists and other humans that designers must collaborate with, but with other organisms that have an agency of their own. Regarding the material's **agency**, Dade-Robertson (2021) explains designing with living organisms would be different from designing a regular machine because the first would be serving an external purpose, while an organism serves its **own interests**. Also, organisms mutate. Zolotovsky (2012) reported experiments that were supposed to be exactly "the same", but yielded different results. She attributes this difference to "probably **spontaneous mutations** during growth" (ZOLOTOVSKY, 2012, p.59). As it would be difficult to predict the final result, the designer has to wait **for the organism to respond to the stimuli** (KEUNE, 2017, p. S4742). In other words, designers would have to wait for the "invisible force" that is materializing the product, the biological organism, whose behavior might be obscure to them (CAMERE, KARANA, 2018). Dew and Rosner (2018) and Collet (2017; 2020) support a design mindset where the material is an **active participant in the design process**. Designers must negotiate. Dade-Robertson (2021) refers to Catts and Zur's 2014 paper "Countering the Engineering Mindset: The Conflict of Art and Synthetic Biology" for the concept of "intolerance to uncertainty" in synthetic biology. To this, Dade-Robertson adds that the practice of synthetic biology is not as precise, it must allow what other authors referred to as "Kludging", "a principle of limited sloppiness" – solutions that are "good enough" but not precise or perfect (2021, p.24).

2.5.4 Thinking systems

On negotiating the best solutions, Daniel Grushkin (2021) writes that biodesigners think **about systems**. He elaborates that designers see themselves in a partnership with the organisms they work with and “that their designed products might affect”. According to Grushkin, a big shift is that the“conception of product **“users” includes the animals that the product impacts** (perhaps in landfill or waterways) and the microbes that live on it and break it down” (2021).

Material Ecology is considered a system of concepts that involves thinking the whole system. It came to the spotlight through MIT’s Mediated Matter Group, in the Media Lab[7]. The core is based on a design perspective that considers that the **design object interacts through different dimensions and environmental variables** (OXMAN et al., 2015). This would establish a more cohesive and coherent relationship between the design object and its environment. The results tend to be complex artifacts, **which are not structured in parts with different functions and materials; they are rather structurally integrated, “grown”, as in nature**. The final artifact is often a **hybrid material solution**, composed of “artificial” and “natural” elements, with the frequent incorporation of living organisms (BADER et al., 2016; MOGAS-SOLDEVILLA et al., 2015; MOSER et al., 2019; OXMAN, 2015; SMITH et al., 2020). This approach applies computational algorithms and technologies, as well as what might yet be considered advanced production techniques, such as 3D printing with “Variable Material Properties” and multifunctional materials. In Material Ecology**,** it might be difficult “to tell apart what is made and what is grown” (MOMA, 2020). Oxman et al. (2015) envision, in Material ecology, that computation, fabrication, and materials would be inseparable dimensions of design.

Templating is a key process in the Material Ecology concept (OXMAN et al., 2015). It refers to the search for patterns in nature and their simulation in a material context to create physical structures (BADER et al., 2015; OXMAN et al., 2015). "**Templates are defined here as**

[7] “The Mediated Matter Group focuses on Nature-inspired designs and design-inspired Nature”. Their work relies on computational design, digital fabrication, materials science, and synthetic biology and is applied to design (MEDIATED MATTER, 2021).

top-down material (for example, physical scaffolds) or immaterial (environmental forces) frameworks that can inform or direct bottom-up processes." (OXMAN, 2015, p.102) Designers would then create natural-like simulations and responses to environmental conditions and stimuli that would guide material disposition and composition. According to Oxman et al. (2015), Templating implies a comprehension of the material synthesis and organization logic. Nature would build artifacts in a “bottom-up” logic, while designers would take a “top-down” approach. This would mean nature parts from an adaptive response of chemical and structural material characteristics to environmental stimuli, therefore a bottom-up system. Mechanisms for this bottom-up form and function expression would be “self-organization, cell differentiation, growth, remodeling and regeneration” (OXMAN, 2015, p.100). Designers would usually start from a top-down approach, a “macro” view of the artifact - beginning by pre-establishing constraints, defining form, parts with different functions to be assembled, and then attributing materials to them (OXMAN, 2015). The author defends this design “paradigm” might also be enforced by the way the industrial supply chain works. **Templating aims to help designers to work in a top-down logic while informed by the bottom-up biological processes**: “this shift in practice requires new methods that offer top-down templates employed to assemble entities for bottom-up formation in a scalable and parallel manner" (OXMAN, 2015, p. 107). The authors name different kinds of templating: (1) **morphological templating**, transitioning into (2) **biochemical templating** and culminating with (3) **biological** as well as (4) **synthetic-biological** templating.

2.5.5 Design process control

In addition to the complexity of thinking whole systems, there is the difficulty of controlling the whole design process when another living organism is participating with its own will. Karana et al. (2018) offer some strategies for dealing with uncertainty in a design project development with living materials. They advise wide **project documentation**, namely the use of a journal: “Noting down every little change in material ingredients or environmental conditions, the student evolved a systematic understanding and a sense of control over what affected which qualities in the material” (KARANA et al., 2018, p.131). Parisi and Rognoli write that "documentation records the process and makes it visible, communicating it [...] (2017, p. 67). Collet (2017) suggests that one option to mitigate uncertainty would be to **design fully controlled environments of growth**, keeping track of variables. She also endorses "**soft control systems** such as those used in bread making" (COLLET, 2017, p.34). Another strategy advised by Karana et al. (2018) is systematically **prototyping** the material at the beginning of the project. They suggest the use of the Material Driven Design (MDD) method, which implies a "Tinkering" step. Tinkering is a systematized experimentation practice to understand the material and its potential. MDD and tinkering are further detailed in the next sections. The same authors recommend **consulting specialists** to speculate possible outcomes and reduce uncertainty. Designers found it to be very important to **collaborate with other experts**, like biologists, and perceived they gained credibility by acquiring other areas' vocabulary (CAMERE; KARANA, 2018). This advice is also given by Cho (2018).

2.5.6 Design representation

Along with project representation to deal with uncertainty and control, **there are design representation issues when the "material" is alive.** Those are raised by authors like Oxman (2010; 2014), Dew and Rosner (2018), Myers (2018), and Sabin and Jones (2018). Dew and Rosner (2018) argue that the distinctions between the digital and the physical are collapsing. Oxman (2010) addressed the correspondence between the digital representation and the physical artifact, proposing with her team a "pixel"- like system. For each "material pixel", or "Maxel", there would be a digital equivalent, a"Voxel", or a "digital material pixel", in the virtual environment (OXMAN, 2010). Oxman (2014), Sabin and Jones (2018), Kirdök et al. (2019), Zhou et al. (2020), and Beyer and Suarez (HBBE, 2021) report the use of the CAD tool Grasshopper inside the Rhinoceros[8] software for making digital representations of their projects. Adding to the design representation challenges with the living, the biodesign process may enter a **nano and micro-scale** (NIYAZBEKOVA; NAGMETOVA; KURMANBAYEV, 2018;

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[8] RHINO GRASSHOPPER. What is Rhino Grasshopper 3D. Available at:< https://www.youtube.com/watch?v=RMF9gSSTOts&t=2s>. Accessed on May 30, 2021.

ANTINORI et al., 2020). Myers considers that scale might impact technology and design even further:

> Just as standardization and manufacturing tolerances to the millimeter scale were crucial to the move from craft to the Industrial Revolution, as well as to the practices and goals of the Bauhaus school, the ability to change the inner functioning of a cell exponentially increases designer's reach, and is enabling a move from the industrial to the biotechnological. (MYERS, 2018, p.14)

Jenny Sabin and Peter Jones's (2018) practice at LabStudio (further described in section 2.6.3) brings some important insights and concepts to the biodesign practice and the biodesign process, especially concerning design representation strategies (visualization). **Their design approach implies design by experimentation, instead of the aim of predetermining a form or solving a problem, results are found in the process**, based on natural systems: "emphasis is placed upon the dynamics of natural systems in context, of behavior and process in the material formation [...]" (SABIN; JONES, 2018. p.363).

To this work mode, Sabin (2018b) introduces the term **Biosynthesis**: While biomimicry would be a goal-oriented approach, biosynthesis would be a **process-oriented approach**, where solutions and applications would emerge along the process (SABIN, 2018b). She explains:

> [...] It is a mode of thinking in design generated through deep immersion within bottom-up processes found in biology and architecture [...] This type of thinking considers biological complexity and formation to emerge through code in context. Here, environment counts in the development of form. [...] (SABIN, 2018b, p. 267).

Traditional language and tools for representing in design would not be sufficient to represent "non-geometric" issues: "In design, notions of change and context are often forced into languages that are not properly suited to their study [...] they inherently produce a gross reduction of systems of far greater complexity [...]" (LUCIA; SABIN; JONES, 2018, p. 216). To tackle this issue, LabStudio has adopted or developed a series of strategies: like **customized software**, "**scaling analysis**", "**non-dimensional numbers**" and **generative software**. Scaling analysis is similar to building a model in scale to make a proof of concept. While non-dimensional numbers might be, for example, a constant, which can "describe the underlying physics independent of size" (NEEVES, 2018, p. 237). Those strategies are used to deal with the micro and nano scales.

Finally, another interesting concept introduced by Sabin is "**digital handcraft**": "our design process moves fluidly between analog and advanced digital procedures, often inserting the human hand or *digital handcraft* in the meaningful and rigorous negotiation of scale and complex behavior" (SABIN, 2018b, p. 271).

2.5.7 A new vocabulary to the language of form

Design representation challenges come when the "material" is alive, but so do challenges in form as well. Myers explains that the change in scale also contributes to a "**new vocabulary to the language of form**", which is expected to rise with the design with the living (MYERS, 2018, p.12). He argues biodesign will develop a "**legible formal language**" (MYERS, 2018, p.14). Collet (2020) further emphasizes that the creative phase would begin with growing the matter while controlling shape and texture.

2.5.8 A fourth dimension: time

Beyond form and scale, in a design project with the living, besides the three spatial dimensions, it is advised to consider a fourth one: **time**. As referenced before, Dew and Rosner (2018) define that an important quality of a living material is the change over time. For these authors, the value of a living material lies in the **potential for change**. This might mean growth, maturing, and transformations to other stages of the organism's cycle that could change appearance, and even decay (KEUNE, 2017; DEW; ROSNER, 2018). Li et al. (2017) and Yang, Gao, and Xu (2020) use the term 4D printing or 4D bioprinting, referring to 3D printed objects that intend some change in **size, form, and/or functionality through time**. Linked to the potential for change, Dew and Rosner (2018) suggest a **performative view of materials**, which would include aging and degradation as a resource, as "temporal potentials". The designer's perception would stand in the core of an interaction, or of **interaction potentials**, considering the material's agency. Designers would describe "scripts" instead of "properties" because properties would not be fixed or stable, there would be only a momentary stabilization in the material qualities (DEW; ROSNER, 2018). Dew and Rosner (2018) propose a "**four-dimensional thinking**" strategy for designers: to think the "two-dimensional drawing" in a "four-dimensional world", considering the weather, time, and others. Grushkin (2021) also describes that biodesigners care about "**time connections**", how design choices affect the other organisms, and what thec onsequences over time might be.

2.5.9 New possibilities in making

Thus, "**Grow-ability**" itself, is also considered **to open manufacturing possibilities** (ZOLOTOVSKY, 2012; CAMERE; KARANA; 2018). An example of this manufacturing potential is skipping binding and gluing processes and growing the artifact directly into a defined shape (CAMERE; KARANA; 2018). Other advantages are the capabilities of self-mending/healing: the organism is able to mend occasional manufacturing accidents that may damage the product (ZOLOTOVSKY, 2012). According to Collet (2020), Camere, and Karana (2018), prototyping in biodesign also means developing the manufacturing techniques to achieve the results in the final product.

Living Construction is a book by Dade-Robertson published in 2021. The book explains in detail many biodesign concepts aimed at designers and architects.

In product design and architecture, assembly and fabrication processes are often seen separately, explains Dade-Robertson (2021). He uses the example of a flatpack bookcase: parts are produced separately to be later assembled. "**If we observe the production of materials from any biological system, it is impossible to make a clear distinction between fabrication and assembly**" (DADE-ROBERTSON, 2021a, p.31). The assembling process follows a continuum and has no separated delineated stages. Dade-Robertson describes biological assembly in terms of the characteristics and interaction of five parameters: (1) Matter, (2) Energy, (3) Force, and (4) Space – through which (5) Information would be the responsible to pattern the parts and forces like an instruction manual. The author proceedes in an analogy, to imagine an alien species. Looking to Earth these alien beings would not understand the difference between human being agents and the flatpack bookcases:

> “what they observe from their spacecraft is an ongoing process of self-assembly. Interactions of different elements of matter produce bookcases spontaneously. For some reason, flatpack bookcases are very useful for our alien species, but they don’t possess the necessary knowledge to understand how to produce them [...]. Instead they want to intervene to allow this spontaneous process to happen but to alter the outcomes such that the resulting furniture matches their specifications” (DADE-ROBERTSON, 2021a, p.33).

There would be a lot we do not know about how living cells work: “**like our aliens, we don’t have the tools to construct the bookshelves, but we might know how to manipulate the information which enables the shelves to be produced**” (DADE-ROBERTSON, 2021, p.33). Dade-Robertson asks – Where is the information for the parts to know how to be assembled? The “design of a biological assembly depends on us identifying where information is located” (DADE-ROBERTSON, 2021, p.47) He provides a detailed description of how the different biological assemblies happen. The author proceeds to explain how the information of the environment affects a multicellular assembly and gives the definition of **morphogenesis**, which would refer to “in the study of multicellular organisms, the process by which cells assemble into patterns” (DADE-ROBERTSON, 2021, p.43). Dade-Robertson (2020) also explains the **emergent behavior**, which has to do with the lack of information neither in the assembly parts themselves nor in the environment: “The patterning of parts gains complexity (and hence information) as the system develops.” (DADE-ROBERTSON, 2021, p.49). Emergence, however, does not mean that the outcome could not be influenced by changing the system’s variables. **In summary: (1) in a molecular assembly: information would reside in the parts themselves; (2) in an assembly of biological molecules: information would also reside in templates; (3) in a multicellular assembly: information also resides in “the environment which is patterned through the interaction between the parts” (DADE-ROBERTSON, 2021a, p. 53). When assembling, the behavior might be emergent, which means information might not be present before the parts assemble, as content would increase as the system develops.**

Dade-Robertson moves forward on how to operationalize these assemblies. He explains that, in biodesign, **reverse engineering would be difficult because**:

> we cannot simply reverse-engineer a hair by only understanding the parts which make up the whole. [...] Understanding amino acids, if we consider them the fundamental building blocks of hair, [this] tells us as much about the structure of hair as a brick tells us about the structure of a house. (DADE-ROBERTSON, 2021, p. 60).

Furthermore, the author discusses the concepts of top-down and bottom-up, and i*n vivo, in vitro,* and *in silico* – which were previously described in section 2.4. According to him, it might be impossible to consider altering any part of the assembly "without referencing other scales of assembly" (DADE-ROBERTSON, 2021a, p.67). Hence, the design problem would be defined in multiple scales: "**the challenge of designing a system of assembly at multiple scales simultaneously**" (DADE-ROBERTSON, 2021, p.68).

2.5.10 The design process with the living phases

Finally, it is important to outline how different authors think of the biodesign phases.

Camere and Karana (2018) report on interviews with 8 "growing designers", the research centers on detailing the perception and general professional profile and presents overall growing design phases:

> 1) a preparation phase, where designers set the conditions for the materials' fabrication; 2) a growing stage, in which the organism fabricates the material; 3) a drying phase, to deactivate the organism and achieve the resulting material; and eventually, 4) the final shaping of the material through different techniques (CAMERE; KARANA, 2018, p. 573)

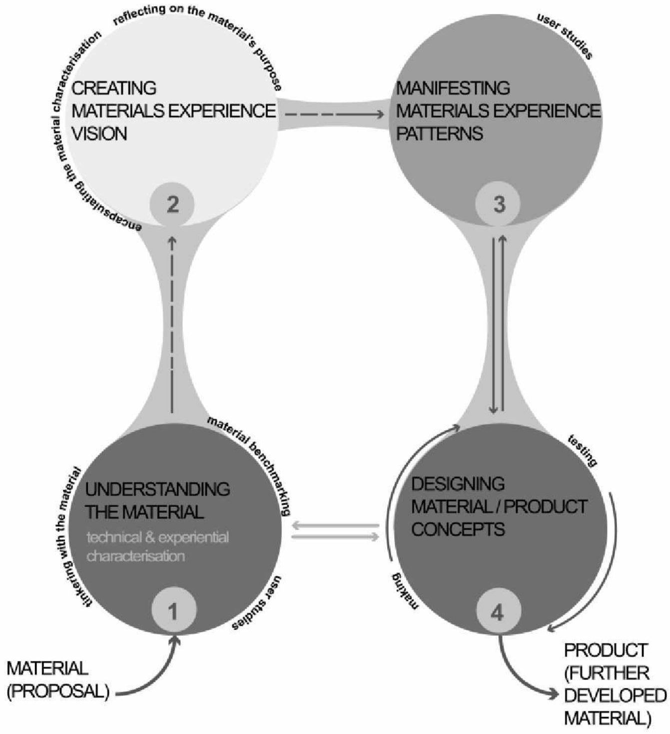
Nancy Diniz (2020b) describes the biodesign process in three steps:

1. Material selection; Material Manipulation;
2. Living system selection;
3. Sterelization; *Modularity*; Innoculation; Incubation; Colonization; *Termination*; Stabilization: Living or Non Living.

Pasold (2020) also summarizes the general design phases in designing with living materials: (1) a first phase of understanding the material, for defining aesthetics and understanding time; a (2) second phase for experimentation in a goal-oriented manner; a (3) third phase to close the ends of what needs further elaboration and a (4) fourth phase to create the outcome (PASOLD, 2020).

Material Driven Design is a method proposed by Karana et al. (2015) and is being used to address design with living materials (PARISI; ROGNOLI; AYALA-GARCIA, 2016; PARISI; ROGNOLI, 2017; CAMERE; KARANA, 2018; KARANA et al., 2018; ZHOU et al., 2020). Its **prerogative is to have a specific material as a starting point in the design process, and then, develop application possibilities, taking the user's experience highly into account.** The emphasis on user experience leads to **user participation in a consultative manner** in various project moments. Figure 8 illustrates the macro phases of this method.

Figure 8 – Material Driven Design Method



Source: Karana et al. (2015, p.40)

The main phases consist of:

1- **Understanding the material:** tasks involve researching the material's origin; technical and experiential characterization (sensorial, interpretative, affective, and performative); possibilities; processes; as well as material benchmarking – in order to understand where the "new" material stands. **Material tinkering** is a key concept in this step; it refers to "hands-on" and practical experimentation and testing with the material (PARISI; ROGNOLI, 2017). The term originates from the Human-Computer Interaction (HCI) field and means "hacking and manipulating physical interaction materials in a naive, playful and creative way [... it] aims to extract data, understand material properties, understand constraints, and recognize its potentialities" (PARISI; ROGNOLI, 2017, p.67);
2- **Creating the materials experience vision:** At this point, a definition of what the design goal would be for this material is developed and translated into a product context with descriptors. The previous steps inform this phase, which summarizes all the information and insights from the investigations with the materials and the users;
3- **Manifesting materials experience patterns:** This refers to finding the product and material application that might successfully express the experience vision. It implies user studies. Karana et al. write:

> The MDD method suggests that the designer should distill one or two experiential qualities (e.g., traditional) from the materials experience vision, and translate these qualities into material and product aspects (e.g., transparency, organic form) based on material experience patterns prevalent among people within the targeted context [Moodboards are examples of tools used for this phase]. (KARANA et al., 2018, p., 128);

4- **Designing material/product concepts:** In this step, more than one alternative of application was analyzed in the case study Karana et al. (2018) describe. These are assessed by ten non-designer people based on a tool to predict product acceptability.

Abreu (2019), described the lack of a research method for interdisciplinary research with microorganisms and elaborated "a method for creating artifacts that use living microorganisms in their constitution or in their production process, designated as Microbioinspired Method (MBI)" (p.21, our translation).

The Microbioinspired project might have as its starter a microorganism, a characteristic of its metabolism, or even characteristics from places and objects where they are present (ABREU, 2019). The methodology includes photographic records, qualitative analyzes, and the creation of a **record book** for the performed experiments and cartographies. **Catalog cards** (Figure 9) are proposed, which contain biological, aesthetic, and sensory information about some selected microorganisms (ABREU, 2019).

Figure 9 –Abreu’s base model for microorganism’s catalog cards (our translation on the right).

CÓDIGO MBI	Nome da espécie do microrganismo

RESUMO

Resumo sobre o microrganismo e suas aplicações em áreas criativas (arte, design, arquitetura, moda...).

CARACTERÍSTICAS BIOLÓGICAS

Características relativas à investigação do microrganismo como:

- Morfologia;
- Genoma;
- Metabolismo;
- Crescimento;
- Evolução;
- Comunicação;
- Motilidade;
- Ecossistema;
- Ecologia;
- Patogenicidade;
- Outras informações biológicas relevantes sobre esta espécie.

CARACTERÍSTICAS FENOTÍPICAS E SENSÍVEIS

Características fenotípicas presentes no microrganismo que chamam a atenção de algum dos nossos sentidos seja a visão, paladar, tato, olfato ou mesmo audição. São exemplos destas características:

- Cor;
- Brilho;
- Textura;
- Cheiro;
- Forma;
- Sabor;
- Outras características sensíveis relevantes sobre esta espécie.

IMAGENS

Apresentação de imagens do microrganismo sejam fotos de microscopia óptica, eletrônica, modelos computacionais, locais onde o microrganismo se encontra, forma das colônias, imagem de projetos que utilizam o microrganismo, dentre outras.

Figura 6. Modelo base das fichas de microrganismos.

Name of the species of the microorganism
SUMMARY
Summary about the microorganism and its applications in creative areas (art, design, architecture, fashion...).
BIOLOGICAL CHARACTERISTICS
Characteristics regarding the research of the microorganism such as:
- Morphology;
- Genome;
- Metabolism;
- Growth;
- Evolution;
- Communication;
- Motility;
- Ecosystem;
- Ecology;
- Pathogenesis;
- Other relevant biological information about this species.
PHENOTYPIC AND SENSITIVE CHARACTERISTICS
Phenotypic characteristics present in the microorganism that capture the attention of our senses, be it sight, taste, touch, smell or even hearing. Examples of these characteristics are
- Color;
- Brightness
- Texture
- Smell;
- Shape;
- Taste;
- Other relevant sensitive characteristics about this species.
IMAGES
Presenting images of the microorganism, be it photos from optical microscopy, electronic microscopy, computer models, places where the microorganism is found, shape of the colonies, image of projects that use the microorganism, among others.

Source: Abreu (2019, p. 25)

Abreu (2019) states that a method for interdisciplinary projects should be **approached more like a network than a linear development**. According to him, **if the interdisciplinary team works together from the beginning of the project, results might be of a higher quality** than if only punctual technical collaborations take place. As a project's lexicon would be of importance in interdisciplinary developments, a **shared glossary** is proposed along with the method (ABREU, 2019). The author also reinforces the importance of the **project manager**'s role to articulate and motivate contributions from all participants. Abreu advocates for not narrowing the project down too much at the beginning: "experiments with microorganisms sometimes present unexpected results, and thus narrowing the working methodology at early stages could restrict the results and guide the research on a single path, leaving its various potentialities unexplored" (ABREU, 2019, p.40, our translation).

The MBI is composed of modules and divided into three macrocycles, called "*Momentums"*. The three Momentums are: (1) 'Momentum Rep', (2) 'Momentum Cell', and (3) 'Momentum Morf'. In each of these Momentums, or cycles, several possible paths might be taken and the parts might be arranged in many different ways. Every project may contain more than one cycle.

(1) Momentum Rep components are explained according to the author:

-R(a) – Microorganism selection: At the selection stage, microorganisms are gathered into six groups: a) bacteria, b) archaea, c) protozoa, d) algae, e) fungi, and f) viruses. Abreu described that "**It is up to the researcher to know a little of each group and think which microorganism best serves the development of the project**" (2019, p.65). He proceeds to offer a quick description of each of these groups according to Madigan et al.'s 2016 "Microbiologia de Brook" (Brook's Microbiology) – presenting visual examples of different species to each of the groups;

-R(b)– Microorganism investigation: The author offers a guide to the "microorganism investigation" stage in momentum rep. He lists: a) Morphology; b) Genome; c) Fisiology (metabolism, growth, motility); and d) Ecology (the inter-relation between organisms and their environment, the ecosystem's characterization, the organism's communication, and their evolutionary path) – explaining every topic with examples;

-**R(c) – Research transversal factors** – Those would be contingencial characteristics of the research, including the researchers' life perspective. Among those possibilities are: philosophical, psychological, social, cultural, economic, historical, demographic, emotional, ethical, and pathological factors: "It is the transversal look to the research that humanizes it and associates the microorganism to reality." (ABREU, 2019, p. 111, our translation);

-**R(d) – Research sensorial factors** – At this stage the researcher must ask "How to sensitize any of the five human senses (hearing, smell, sight, touch, and taste) through the use of microorganisms?" (ABREU, 2019, p.112, our translation). It includes, aside from colors, textures, brightness, tastes, smells, and sounds; even the more abstract factors such as memory, desire, emotion, and intuition;

-**R(e) – Problem, artifact, and process** – Not all project problems begin the same way and might even not be fully clear and defined at the beginning (ABREU, 2019). Abreu (2019) explains that the problem might begin with the choice of the artifact to be developed; or the selection of the microorganism; or the desire to develop a new production process. At this research stage, project references and inspirations might also mobilize the beginning of micro-bioinspired research.

Proceeding with the details on MBI's stages, (2) Momentum Cell is the stage in which the information explored in Momentum Rep must be organized and filtered to create a project focus (ABREU, 2019). At this stage, the author recommends that the researcher evaluates the project's steps so far and assesses the next necessary steps, including project deadlines, risks, and budget. At Momentum Cell, the recommendation is that an interdisciplinary team must be assembled if it was not created yet (ABREU, 2019).

Finally, (3) Momentum Morf refers to the project's execution, where the artifact comes to life. Momentum Morf's elements, according to Abreu (2019) are:

-**M(a) – Techniques, tools, and experiments** – The author explains the meaning of those three concepts in the MBI. Experiments would be more freely conducted and could involve tools and techniques. Techniques would refer to several rules that might lead to efficiency and predictability. Tools would be physical or abstract mechanisms used by the researchers to execute a named task. Microbiology tools and techniques examples would relate to microbial growth, genetic analysis, and microscopy. Design tool examples would be brainstorming, competitor analysis, and reference boards;

- **M(b) – Results and analysis** – This is the step in which the result's data are treated and analyzed. This would be the moment to compare results with other research and the literature. Here, improvements, simplifications, parametrizations, and specifications are considered;

- **M(c) – Problems** – When working with living systems, a series of problems may appear and their solution might be tied to the time and resources available for the experiments (ABREU, 2019). Abreu (2019) lists some of the most common problems: not being able to grow the organisms correctly; not having access to adequate equipment, laboratory infrastructure, and necessary supplies to grow the organisms; not obtaining the expected results even in predictable settings. The author offers some alternatives, such as beginning by decomposing the problem into manageable variables; using alternative tools, similar equipment, and experiments – even if this leads to not fulfilling completely the project's objectives. Sometimes it could be necessary to return to Momentum Rep and select another microorganism or even study the selected one more in-depth, looking for other properties (ABREU, 2019);

- **M(d) – Discussion** – After some stability in the data is found, or the artifact's conclusion, an evaluation of the whole process and the artifact takes place (ABREU, 2019). The recommendation is to ask: Did the developed artifact solve the problem defined in moment cell? What kind of impact may the artifact have on science and society?

- M(e) – Perspectives – Future works and improvements.

Some research resources for more straightforward information to work with microorganisms are also provided. Abreu (2019) points out that for every microorganism, there would be a **biosecurity level**. Microorganisms might be bought from a microorganism bank; exchanged in partnership with microorganism banks or universities; or even collected in the environment (ABREU, 2019). Finally, the author indicates laboratory manuals, or microbiological methods books, such as "Benson's microbiological application" by Brown & Smith (2017), "Microbiological diagnosis" by Konemam (2008), or even specific ones such as "Microbial examination methods of food and water" by Silva, Tniwaki and Junqueira et al. (2018). These manuals describe the experiments and assist in interpreting data and preparing materials and are used as guides for practical microbiology classes, such as the book "Microbiology: manual of practical classes" by Filho and Oliveira (2007), published by the Federal University of Santa Catarina.

2.6 -TEACHING AND LEARNING DESIGN WITH THE LIVING

To give an overview of biodesign teaching and learning, this section begins with an introduction describing the literature review on the subject by Anke Pasold (2020). Next, a systematic review of biodesign masterclasses, courses, undergraduate programs, master's programs, and Ph.D. programs in formal education is provided. Finally, other biodesign teaching and learning constellations are introduced, like the Biodesign Challenge, the Cluster of Excellence Matters of Activity and Sabin, and Jone's LabStudio.

Prof. Dr. Anke Pasold, Associate Professor at Copenhagen-based Material Design Lab, makes a literature review on "Advanced Growing Materials", and draws an overview of the teaching and learning scenario for biodesign (PASOLD, 2020).

According to her: "**designing with living matter is, by its very nature, designing with complex, open systems**" (PASOLD, 2020, p. 135) – hence, learning approaches from systems design seems a logical connection to be made. Pasold (2020) cites Chen and Crilly's 2016 "Describing complex design practices with a crossdomain framework: learning from Synthetic Biology and Swarm Robotics" to list the established characteristics of complexity that designers will have to work with: **(1) the system's unpredictability, (2) context dependency, (3) noise, (4) emergence, (5) stochasticity, (6) non-linearity, (7) crosstalk, (8) open systems, (9) overlapping hierarchies, (10) incomplete understanding, and (11) possible multiple characterizations**.

To tackle complex systems designers would have to (1) **map the systems correlations and find out patterns** that might be interesting for the design process; and try to find (2) boundaries, to **define a design space** – understanding, for instance, how the material behaves biologically – and sometimes this can be only achieved through experimentation (PASOLD, 2020). Pasold (2020) cites Chen and Crilly's once again to explain the two approaches that establish "a sense of control to effectively design within the network of parameters at hand" (PASOLD, 2020, p.138). These would be (a) Rational design approaches and (b) Black box design approaches (PASOLD, 2020). **Rational design approaches** include **(a1) the reduction to a number of conditions to be explored individually to establish patterns; (a2) the learning through designing and making experimentation as part of the whole design process; and (a3) the integration of multiple characterizations from different sources (from different disciplines)** (PASOLD, 2020). In addition, **Black box design approaches aim at making things more concrete** – one strategy would be to clearly define requirements (PASOLD, 2020). These principles seem to align with educational contexts to "prevent students from stranding in the pool of sheer endless possibilities" (PASOLD, 2020, p.138). Continuing to cite Chen and Crilly's work, Pasold (2020) explains that: "the most important conclusion from the working with complexity, however, is the recorded manifestation that **only by working and therefore designing with the system, at whatever level of complexity or isolation, will we gain a better understanding of the very same**" (PASOLD, 2020, pp. 139-140). This would be aligned with the more hands-on approaches to design with. Finally, **simulation** would be an important resource to tackle complex, open systems (PASOLD, 2020).

The author explains that part of the strategy used in education in design with living materials is the use of very **hands-on – experimental and experiential approaches - and do-it-yourself open resources** (2020). Formal input "in **form of lectures and tutorials** is not excluded from the syllabus and is seen as a way of building a base level of understanding, subject placement, general introduction and introduction of the respective other [...]" (PASOLD, 2022 p. 141). **To gain an in-depth understanding of the material consumes a good part of the projects and is considered an indispensable foundation** (PASOLD, 2020).

Educational biodesign practices usually combine lab and studio activities. Process documentation is detailed and illustrated, often in the form of a **project journal, or a design**

catalog (PASOLD, 2020). The continuous inclusion of **interdisciplinary expert assistance and feedback** is common to all phases (PASOLD, 2020).

To enable design with living materials, Pasold writes that "It has been established that there is an inherent need for cross-disciplinary knowledge, communication and engagement [...]" (2020, p.147). Enabling design with living materials would concern: (1) **new ways of thinking**, which refer to a (1.1) new mindset and a (1.2) new role; and (2) **new ways of working**, which comprise the dimensions of (2.1) frame, (2.2) collaborative learning, (2.3) communication, and (2.4) coordination (PASOLD, 2020).

Concerning the (1.1) **new mindset**, it would be "the basis for learning and effectively working and creating within this new frame" (PASOLD, 2020, p.148). It relates to an understanding of the interdisciplinary, open, complex nature of the projects. This mindset includes appreciating to enter "a new way of designing; material first, product synchronously after" (PASOLD, 2020, p.148), which deals with time issues, lack of control, experimentation, working with professionals from other disciplines, learning new language and vocabulary (PASOLD 2020). With this different mindset, designers would assume a (1.2) **new role**, really connected to the "making" of the material, a co-creation with the other organism, different from the one from the "learned fashion" (PASOLD, 2020, p.149).

Regarding the (2.1) **frame**: there would be a higher demand for what would be a "**proper setup**" (PASOLD, 2020, p.149). The setup would refer to physical spaces for designing, such as labs and resources, and the establishment and facilitation of expert network(s), like advisors, and/or open-source materials (PASOLD, 2020). About (2.2) **collaborative learning**: "part of the systemic didactic approach is that complex and new knowledge is learnt in collaboration and co-teaching sessions that enable peer review as well as external analysis and criticism" (PASOLD, 2020, pp.149-150). Expert feedbacks also help the project to develop faster, and more effectively, and might be useful to validate results (PASOLD, 2020). Pasold gives some ideas on how to facilitate collaborative learning: cross-disciplinary project setups, exchange periods, and the integration of teaching staff from other disciplines (PASOLD, 2020). In this context of collaboration, **an appropriate glossary** is crucial for (2.3) **communication**. An agreement on terms and definitions would be an interesting proposition (PASOLD 2020).

Finally, (2.4) **coordination**, which would refer to checking in and following along a plan (PASOLD, 2020).

2.6.1 Formal Education

To map the teaching and learning of biodesign in formal education, a systematic review was made. The full paper describing the methodological procedures and results is presented in Appendix 9. The paper offers an analysis of each initiative containing course load, course infrastructure, and a course overview.

Some of the findings of the paper are:

- **Course load varies greatly among institutions**. One example in master's programs is that Arizona State University requires 30 credit hours and a thesis, while the University College London requires a total of 300 credits;

- A highlight in infrastructure is the University of the Arts London, which offers a containment level 1 biology laboratory, a biologist in the teaching team, an international network, and knowledge exchange with industry partners. (UAL, 2022).

- In the course overview, a number of 5 institutions emphasize **lab work** (TUDELFT, 2023; UWA, 2022; UAL, 2022; UCL, 2022; ASU, 2022). An interesting example is the Arizona State University (ASU, 2022), where students rotate between laboratories in order to define a research interest and an advisor. Furthermore, **ethical implications** are also mentioned in the curricula of 5 universities (THE UNIVERSITY OF SIDNEY, 2023; THE UNIVERSITY OF SIDNEY, 2022; UWA, 2022; ASU, 2022; UWA, 2022). **Project/studio** structures are a practice in 7 of the initiatives (UPENN, 2023; PINTO; PUGLIESE, 2017; ASU, 2022; THE UNIVERSITY OF SIDNEY, 2022; UNIVERSITY OF CINCINNATI, 2023; UNIVERSITY OF CALIFORNIA, DAVIS, 2023; ASU, 2022). **Interdisciplinary experience** is in course development at 6 institutions (THE UNIVERSITY OF SIDNEY, 2023; THE UNIVERSITY OF SIDNEY, 2022; UWA, 2022; UCL, 2022; ASU, 2022; UAL, 2022). **Prototyping** another seems an important practice, mentioned by 5 of the universities (UPENN, 2023; THE UNIVERSITY OF SIDNEY, 2023; UNIVERSITY OF CALIFORNIA, DAVIS, 2023; UNIVERSITY OF CINCINNATI, 2023; THE UNIVERSITY OF SIDNEY, 2022). **Market-driven/application-driven solutions** are mentioned in the TUDelft (2023) and the University of California, Davis (2023) curricula. The University of Sidney (2023) and the University of the

Arts London (UAL, 2022) focus on **project communication skills**. Four universities had activities oriented to participation in the **Biodesign Challenge** (2023) (UNIVERSITY OF CALIFORNIA, DAVIS, 2023; UNIVERSITY OF CINCINNATI, 2023; THE UNIVERSITY OF SIDNEY, 2022).

Two examples are given in more detail next: the European Central Saint Martins at the University of Arts London and the Latin-American Universidad de Los Andes, Colombia.

Central Saint Martins at University of Arts London

At Central Saint Martins at the University of Arts London, the whole biodesign structure is shared between the Master of Arts Biodesign, the Master of Art and Science, the Master of Arts Material Futures, Ph.D. students, and visiting researchers. There are many intersections between the different modalities, and the disciplines of art and design work together. The Master of Arts Biodesign (MA Biodesign) focuses on "pushing the boundaries of sustainable design via biomimicry and biological sciences" (UAL, 2022, p. 6). At the "Living Systems Lab - A symposium by Central Saint Martins – UAL" (MAAT, 2020), Heather Barnett, Nancy Diniz, and Carol Collet share their teaching and learning experiences at the MA Biodesign.

The Grow **Lab is a central reference to the MA Biodesign program**: "it is really about learning how to observe microorganisms and manipulate them - into incorporating these into design thinking and making" (DINIZ, 2020a). Diniz explains that it involves **training the students in a new language of visualization and representation, which is not apprehensible by the naked eye** (2020a). This is made with the help of "software packages which are not usually available for designers" (DINIZ, 2020a). In the laboratory, microscopy, and biochemistry notions are presented to the students. Diniz argues that these are seen as a "**new way of drawing", a new design language in development in biodesign practices** (2020a).

Heather Barnett introduces that

> When working with living systems, it is important to observe and learn from the organism. You cannot impose your will upon another life form to get it to perform for you, to fulfill your creative aspirations. You need to work with it, to try to understand its needs, to speculate on how it understands its surroundings (BARNETT, 2020)

According to Barnett, this takes time and requires the practice of small observations. She develops a practical exercise in her talk: "**Small acts of being**". The exercise is part of a project and was developed in a collaboration between artists Heather Barnett, Sarah Christie, and philosopher Betti Marenko (BARNETT, 2020). The instructions are:

> 1 – When you are instructed, wander into your environment and find another living thing;
> 2- Tune into this other form of life and observe it closely;
> 3- Think about what it perceives, how it senses, how it understands time;
> 4- Think about what it knows of your existence and how you relate to it;
> 5- You can photograph it, or photograph the place where you found it (BARNETT, 2020).

Diniz summarizes that in their practice at MA Biodesign, the work is "**very much about manipulating materials through computational design processes and then selecting microorganisms where you can grow on these materials and then biofabricate modular systems. So modularity is kind of the way we scale up the prototypes**" (DINIZ, 2020b). The program is interested in questions like: "[...] how do we combine living with a synthetic environment? How do we provide a synthetic scaffold where this material can thrive, can grow, can interact with the environment? [...] how these things can integrate our daily lives?" (DINIZ, 2020b). Finally, Diniz shows how they explore form through computational design processes, simulating natural patterns: "[...] create digital simulations of different living organisms. We employ different computational techniques including particle and agent-based simulations to study emergent behavior and growth patterns" (DINIZ, 2020b).

Universidad de Los Andes, Colombia.

Led by the microbiologist and professor Giovanna Danies Turano, the Andes University in Colombia has three activity modalities in which biodesign teaching and learning happens: (1) an Extension program; (2) an Undergraduate degree; and (3) a Master's program. In a conversation with professor Turano[9] and her team, they explained how the biodesign course within the undergraduate degree worked. The course is usually taught by more than one professor or lecturer, generally 2. It takes 16 weeks (or one semester) and is offered to students in the 3rd year. According to Turano, they **follow the Biodiseño en Colegios structure** (summarized below) and **follow the Biodesign Challenge Rubric** (Appendix 5). The course's premise does not begin with the collaboration with another living organism or does not part from a material perspective. The professors rather give students themes to work on, like "food", or a sci-fi movie. The projects developed by the students must address a **UN Sustainable Development Goal as a problem starter**. The idea is that students work with a more social orientation in their projects. In the course, it is common to have guests over to bring new perspectives to the projects, such as business professionals and scientists.

Biodiseño en Colegios

"Biodiseño en Colegios" might be considered a complete facilitating artifact for teaching and learning biodesign, the aim is to reach high school students and develop their empathy with nature. However, the sense of the "Biodiseño" concept seems to be closer to the biomimicry dimension, instead of the sense of meaning a collaboration with other living organisms. Turano et al. (2020) present the material in the form of a book. The design process method proposed is based on Design Thinking.

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[9] On the 28th of June, 2021, I had an informal online meeting with professor Giovanna Danies Turano, professor Karen Aune, professor Maria Paula Baron Aristizabal, and Jenny Grillo Naranjo to discuss the possibilities of implementing Biodiseño en Colegios in Brazil. They also described how they work in teaching and learning biodesign at the Universidad de Los Andes in Colombia.

Biodiseño en Colegios proposes constant ethical reflection with the concept of **Bioempathy**. Many Bioempathy principles are explained in the book (e.g., Autonomy, No Discrimination). Biodesign phases consist of **(1) Exploration, (2) Interpretation, (3) Ideation, (4) Testing, (5) Evaluation, and (6) Communication**. Each of them is fully detailed in a chapter with design tools, such as photographic journals, system maps, and observation guides. Turano et al. (2020) develop supporting cards to help teachers guide the design process and reflections with students. The card themes are (a) the UN's Sustainable Development Goals, (b) Users, and (c) Contexts. Cards are supposed to be combined to provide project starting points. Additionally, the material offers a briefing model to be filled by the students with project information and requirements. Instructions for every situation are presented, like decision-making. The book has a chapter explaining important biology concepts, like biotechnology and biomimicry principles.

Following in the next sections, other biodesign teaching and learning constellations are presented.

2.6.2 »Matters of Activity. Image, Space, Material«

The Cluster of Excellence »Matters of Activity. Image, Space, Material« (MoA) is a project dedicated to studying matter, the substance of things, as an **active subject – with its own agency** (MOA, 2018). To this object of study, MoA **gathers experts around thematic projects mixing disciplines** ranging from material science, biology, cultural studies, art history, philosophy, and design disciplines (2018). Many projects in the Cluster involve the collaboration with other living organisms. The Cluster is hosted by Humboldt University in Berlin, but many other universities and institutions participate in it. It could also have been categorized in the formal education section because it organizes a Master's and Ph.D. program – however, it is categorized as another kind of constellation due to its unique ethos and structure.

According to the website, the Cluster focuses on **a new culture of the material**, a theory and practice of "matter", with the reinvention of the **material as active matter** (MOA, 2023). To this focus comes the rethinking of the relationship between the analog and the digital. MoA members "[...] develop images, spaces, and materials as active construction elements of a new physical and symbolic reality, **in which nature and culture are intertwined in a novel way**" (from MoA's 2018 project summary, p. 122).

Six main projects are fomented by the cluster, which offers a common ground and open space for the participants of the multiple disciplines to meet and develop together. There are three projects about elementary practices: (1) Weaving, (2) Filtering and (3) Cutting – and there are projects which create unity around the theory and the practice: (4) Symbolic Material, (5) Material Form Function and (6) Object Space Agency (MOA, 2018). Within these projects, researchers group on smaller initiatives, like developing a structure, a technique, or a theoretical study.

The research methodology combines experimentation, theoretical, and historical analysis and design processes. The research process is centered in *Gestaltung* and focuses on making: "we consider making a highly sophisticated integration of epistemological theory, experimental practice, design strategies, enactive thinking and structural operations [...]" (from MoA's 2018 project summary, p. 123)

Resulting products of the cluster are a series of materials, techniques, and theories. These assume the form of publications, events, course programs, exhibitions, and others - and include a Ph.D. program and a Master's program with international collaborations (MOA, 2018).

2.6.3 LabStudio

LabStudio intersects the concept of a studio and a laboratory in interdisciplinary work – it was founded by Jenny Sabin and Peter Jones and resulted in elective courses in undergraduate education. This initiative could also be categorized in the formal education section, but again, it has a particular structure that could be considered a unique constellation. The lab had an initial mission and research agenda:

> Overall, the mission of LabStudio is to foster new and ongoing dialogs between the disciplines of architecture and biology, and to jointly investigate fundamental processes in living systems, connect their historical and contemporary relationships to generative design and fabrication in architecture, and innovate their potential application in architecture and biomedicine (SABIN; JONES, 2018, p. 49).

Sabin reinforces that one of their main deliverables is a truly shared process and **collaborative space** (SABIN, 2021). The preliminary work in the lab set the foundation for a "[...] graduate course entitled, "Nonlinear Systems Biology and Design" (2007–201[0]), jointly housed in the Department of Architecture, School of Design, and the Institute for Medicine and Engineering, UPenn" (SABIN; JONES, 2018, p. 2). Sabin gives more detail to a later version of this seminar, taught by her at Cornell University within the Department of Architecture and titled: "Special Topics in Construction: Bio-Inspired Materials and Design." (SABIN; JONES, 2018, p. 50). According to her, the course "investigates biologically informed design through the visualization of complex datasets, digital fabrication, and the production of experimental material systems for prototype speculations of adaptive building skins" (SABIN, 2018a, p.239). The course assumed the form of part of a seminar and part workshop. In the seminar, specific biological concepts were provided. Students were encouraged to find basic rule sets in biological systems – to be later applied in the workshop. These rules were then used to develop visualizations, including 3D-printed models. (SABIN, 2018b). The pedagogic framework was based "upon a detailed understanding of systems biology, and corresponding explorations in generative design and experimental fabrication in architecture" (SABIN; JONES, 2018, p. 52). The approach, according to Sabin, was to establish **interdisciplinary dialogues** and to favor "**process-driven research over goal-driven research**" (SABIN; JONES, 2018, p. 52). Pedagogical procedures were: "lab meetings, readings, and field trips to inter-disciplinary research laboratories" (SABIN; JONES, 2018, p. 52). The project work follows three methodological trajectories:

> - Visualization and simulation: The generation of digital design tools, whereby cellular-mediated changes in pattern, geometry, material, and environment are simulated in 3-D digital environments via custom-written architectural algorithms. These models and simulations visually describe the dynamic and nonlinear human cell behaviors and processes being researched in 3-D and 4-D space/time.
> - Experimental material systems: The abstraction and application of nonlinear and dynamic cell behaviors to the experimental design of materials and geometries at the human scale with maximum response to environment leading to a catalog of surface effects (e.g., color or pattern change).

> - Generative fabrication: Transformation and translation of the design ecology developed in the first two phases into the design and fabrication of a series of analogic prototypes that are materially directed. These may include experimental and responsive systems that function at the human and architectural scales. The final fabricated physical models are composed of hybrid material systems that may include 3-D printed components (SABIN; JONES, 2018, pp. 52-3).

The courses invited experts and critics to comment on the student's projects. The authors mention the use of software like GenerativeComponents [GC] by Bentleyyt, and RhinoScript (SABIN; JONES, 2018).

Sabin and Jones list a number of questions that could work as design requirements for a living system:

> -How would an architect provided with as many as 30,000 individual building blocks of different shapes and sizes, which interact in multiple ways with one another and with their surrounding environment in time and space, design a final form that is unique on its exterior, yet is relatively uniform at its core, at certain scales at least? As an additional part of the brief, the architect is instructed that the fully self-assembled, modular structure needs to have a personality, be intelligent, regenerative and appealing, while retaining a memory of the intermediate processes that gave rise to the ultimate form.
> -What if the client dictated that this design goal always had to be met on time, with minimal cost and energy, yet with a high degree of reproducibility and fidelity, using a slightly different version of the original blueprint for each and every project?
> -What if many parts of the structure had to execute more than one function at a specific moment in time, even at the same or a different location within the developing and final configuration?
> -What if the rules of engagement between the emergent and final form, and the immediate and larger environment, continually changed at all phases of building, and at every possible scale and time-point?
> -How would the designer and engineer manage a structure that is continually relocating from one city block to another, as well as to one that is constantly being remodeled and rewired from within?
> -How would the form appear if the client decided to selectively remove or modify one or more of the building blocks during construction, or even after completion of the structure, without the designer's input?
> -What if every form and structure represented in the designer's portfolio always had to influence those of subsequent generations? (SABIN; JONES, 2018, pp. 47-8)

2.6.4 Biodesign Challenge

The Biodesign Challenge (BDC) is an "international competition and education program for high schools and universities that introduces students to the intersections of biotechnology, art, and design" (BDC, 2021). According to the BDC (2021), its goals are: "(1) to create a community of collaboration among artists, designers, and biologists; (2) to seed the first generation of biodesigners; and (3) to build a meaningful public dialogue about biotech and its uses". It had its first edition in 2016 and is sponsored by companies like Google, Science Sand Box, Ginkgo Bioworks, and others (BDC, 2021). Schools and universities might register for the program and the classroom gains access to BDC resources (library and webinars) and mentor network - and develop projects "**that explore biotechnology's role in sustainability, fashion, agriculture, architecture, biomaterials, medicine, water, ethics, and more**" (BDC, 2021). Classrooms are divided into teams of maximum of 6 students. After participating in the challenge, students become part of the alumni. There is a summit, which happens every year in June, where projects are presented to a public of "prominent artists, designers, curators, scientists, entrepreneurs and an audience of over 5,000" (BDC, 2021).

The BDC offers guidelines to develop a biodesign project:

> 1. First: **do the research!** What cultural issues are you responding to? Are you posing a solution or raising a question? Are you focused on a community that exists today or a speculative world that could exist in years to come?
> 2. Whether you're creating a speculative project or a solution-based one, **you should identify the groups** that your design will serve and include. How does your project respond to the unique aspects of this target community? If you can, you should meet the people you're designing for
> 3. If your project is critical, **what is the critique?** How do you aim to influence your audience (in this case, the BDC community)? What is the question the project poses? Does it pose a call to action?
> 4. Remember, BDC isn't a pitch competition. Share both your accomplishments and shortcomings. What works, **what needs to improve**, and what should be the next steps for your project? Be honest with your audience and with yourself!
> 5. Successful teams **reflect on their experience**. Consider the thought process that led to your idea. Can you identify biases, assumptions, and a set of values in your project? Does the project change if viewed in different contexts or if you change the assumptions? We **value perspectives** from individuals across diverse backgrounds including gender, race, socioeconomic status, and life experience. What other perspectives and voices should contribute to the idea? (BDC, 2021)

Each year, the judging of the projects occurs in two rounds. The first round happens at the end of the academic semester, when BDC instructors and expert consultants, who have worked with the classroom, choose one team to present at the BDC summit (BDC, 2021). During the summit, the project's videos are broadcasted and in the sequence, BDC judges ask questions to the teams. The judges assess the projects following a rubric that considers

concept, presentation, reflection, and context. The complete rubric is presented in Appendix 5. The next chapter presents the Methodological Strategy.

3 METHODOLOGICAL STRATEGY AND PROCEDURES

This chapter is dedicated to detailing the methodological strategy and procedures followed throughout the thesis. The research was previously approved in a qualification exam on 25 July 2021 – and at the local Ethics Committee on 19 October 2021 - CAAE 51392921.0.0000.0102, review number 5.045.602. Figure 10 presents its overall structure.

Figure 10 – Methodological Strategy and Procedures chapter overview

Chapter overview

1. Introduction	2. Design with the living concepts, and practice	3. Methodological strategy and procedures	4. Lessons on the biodesign process	5. Discussion	6. Conclusion	Appendix
		3.1 Design Science Research 3.2 Phase 1 – Problem and Context 3.2.1 Systematic and narrative literature reviews 3.3 Phase 2 - Related Artifacts 3.3.1 Design process analysis framework 3.3.2 Interview protocol 3.4 Phase 3 - Development 3.5 Phase 4 – Evaluation 3.5.1 Matters of Activity				

Source: Illustrated by the author (2023)

The research problem is summarized in the question: **How to facilitate teaching and learning the biodesign process in a limited resource undergraduate education context?** To answer it, this work draws on the **Design Science Research (DSR) methodological strategy**, described by Dresch, Lacerda, and Antunes Jr. (2015). This choice[10] is based on the DSR nature, which implies the development of an "artifact that solves a domain problem, also known as a

[10] The methodological choices are briefly explained here by comparing them to other methods, based on Dresch, Lacerda, and Antunes Jr. (2015) and Dresch, Lacerda, and Miguel (2015). Mazzarotto Filho (2018) also follows these arguments for his methodological choices. The Case Study method is not considered for this research because it would presuppose no interference from the researcher. As for Action Research (AR), it would indeed imply intervention and the participation of the researcher, which is in the scope of this study. However, AR supposedly generates knowledge on "how things are or how they behave" while DSR generates knowledge on "how things should be" (DRESCH; LACERDA; MIGUEL, 2015, p. 1129). Additionally, AR would refer to a specific situation, while DSR would be "Generalizable to a certain Class of Problems" (DRESCH; LACERDA; MIGUEL, 2015, p. 1129).

solution concept, which must be assessed against criteria of value or utility" (FORMOSO, 2015, p. v). Furthermore, the strategy is also used by other researchers that aim at educational contexts in design, to name a few, Ferreira (2018), Mazzarotto Filho (2018), and Costa (2019).

Considering authors may diverge when characterizing the research theoretical framework (ANFARA, 2008), the choice here is to follow Gray's categorization, who in turn supports his work through literature review (2004). In consonance with the **theoretical perspective** Gray draws, this study could be located in the **phenomenological** perspective, as it focuses on the participant's experience and interpretations, as well as the researcher's. The **research orientation** would be set as **applied**, as opposed to fundamental or basic research – because it has a practical focus and aims at the development of a solution (GRAY, 2004). Regarding the **collected data**, it would be mainly a **qualitative** research – dealing with data in context, in-depth, and open to multiple interpretations (GRAY, 2004). Still following the same author, the research purpose would qualify as **exploratory and descriptive**, as opposed to explanatory. It is exploratory in the literature review and in the interviews of the experienced designers – because it seeks to "explore what is happening and to ask questions about it" (GRAY, 2004, p. 32). It is descriptive when it tries to underline the biodesign process models, trying to provide a "picture" of things as they are (GRAY, 2004, p.32). To add Dresch, Lacerda, and Antunes Jr.'s angle (2015), the research purpose could be also mainly argued as **prescriptive** as well because the framework would be a "prescription" to a specific problem. As for the methods and reasoning, it would be mainly characterized as **inductive** since it allows a (limited) generalization of the results, seeking for patterns, consistencies, and meanings (GRAY, 2004). Although it is mainly inductive, the reasoning would be **deductive** in the artifact's evaluation phase – because it tests an a priori hypothesis (the learning objectives in the framework) (GRAY, 2004). Dresch, Lacerda, and Antunes Jr. (2015) further describe DSR as an **abductive**[11] process, as its nature consists of creative reasoning to propose theories and "explanatory hypotheses for a given phenomenon/situation" (like a framework) (p.61). Table 3 presents an

[11] The authors explain the difference between the reasoning approaches or methods: Inductive would state "from what is"; a Deductive approach would state "what should be", while Abductive reasoning would "suggest what can be" (DRESCH; LACERDA; ANTUNES JR., 2015, p.62). The deductive method would be better suited when logical reasoning is required.

overview of the characterization throughout this study's objectives and phases, which will be better presented in the following section of this chapter.

Table 3 – Research characterization

RESEARCH PURPOSE AND REASONING CHARACTERIZATION	DSR PHASES	OBJECTIVES
Exploratory - Objectives 1-7; Descriptive - Objectives 1-5	1. PROBLEM AND CONTEXT	
Abtuctive - Phase 2; Prescriptive - Objectives 2-9	2. RELATED ARTIFACTS	**O1-** To identify artifacts related to the representation and description of the biodesign process and biodesign teaching and learning; **O2-** To underline didactic biodesign process models based on interviews with experienced biodesign professionals;
Deductive - Phases 3-4	3. DEVELOPMENT	**O3 –** To define the requirements for the teaching and learning facilitating artifact; **O4-** To formulate the framework for teaching and learning structure and elements; **O5-** To establish an evaluation rubric for the proposed framework and its outcomes;
	4. EVALUATION	
Inductive - Phase 5	5. CONCLUSION	

Source: Elaborated by the author (2021) based on Gray (2004) and Dresch, Lacerda and Antunes Jr. (2015)

The following sections provide more detail on how this study unfolds based on Design Science Research and include the supporting methodological procedures.

3.1 DESIGN SCIENCE RESEARCH

According to Dresch, Lacerda and Antunes Jr. "Design science research is a **method** that establishes and operationalizes research when the desired goal is an **artifact** or a recommendation" (2015, p.67). The solution would be a **prescription** generalizable to a **Class of Problems** and should pursue **pragmatic validity,** in other words, to solve the proposed problem. Likewise, this solution is expected to meet the needs of different actors interested in the system, to respect the context and consider costs and benefits.

The **Class of Problems** is a concept described by the authors as the enabler of a certain level of knowledge and theory generalization - "we define Class of Problems as the organization of a set of problems, either practical or theoretical, that contain useful artifacts for action in organizations" (DRESCH; LACERDA; ANTUNES JR., 2015, p.104). The Class of Problems is connected to the artifacts **Contingency Heuristics.** Contingency Heuristics relate to the formalization of the artifact's limitations considering the environment in the implementation phase (DRESCH; LACERDA; ANTUNES JR., 2015).

Based on their literature review, Dresch, Lacerda, and Antunes Jr. (2015) outline and characterize the concept of artifact, which would be the result of the method. The artifact is described as an artificial organization of a system's inner components. This artifact aims to fulfill expectations in an outer environment. The authors present five artifact forms: **constructs, models, methods, instantiations** or **design propositions** (DRESCH; LACERDA; ANTUNES JR., 2015). To answer to the problem of this study, a possible artifact would be a method, which is supposed to transform and improve a system, it might be graphically represented and could be ecapsulated in heuristics (LACERDA et al., 2013; DRESCH; LACERDA; ANTUNES JR., 2015). However, a method seems too rigid of a structure considering the needs of teachers, lecturers and professors. So it was decided that the facilitating artifact would be a (1) **framework**, which according to the Cambridge dictionary means: "a supporting structure around which something can be built" or a "a system of rules, ideas, or beliefs that is used to plan or decide something" (CAMBRIDGE 2022). **The framework aims to facilitate teaching and learning the biodesign process in a limited resource undergraduate education context.** A support artifact is a necessary outcome for achieving the frameworks: (1.1) **models**, which are "a representation of how things are" (DRESCH; LACERDA; ANTUNES JR., 2015, p.109), to act as case-studies inside the framework. These models seek "**To underline didactic biodesign process models based on interviews with experienced biodesign professionals**", which refers to the sixth specific Objective (O2) in this thesis. Three other studies lay the foundations for developing the models regarding the design process in general. The first one is the Design Council's "Eleven Lessons in Design: A study of the design process", which "aimed to draw out some of the key features that define the state-of-the-art in modern design practice" (DESIGN COUNCIL, 2007a, p.1). That study resulted in the **Double Diamond** framework. The second study is Rozenfeld et al.'s (2006) **Product Development Process (PDP)** from the book: "*Gestão de desenvolvimento de produtos: uma referência para a melhoria do processo*" (Managing product development: a reference for process improvement, our translation). The third study is Kim and Lee's **Mosaic Method**, recommended to "determine actual design process at best level" and is argued by the authors as "applicable to the discovery of other design processes" (KIM; LEE, 2017, p.257). More on how these support procedures and methods will unfold are further elaborated later in this chapter.

The original DSR 12 phases according to Dresch, Lacerda and Antunes Jr. (2015) are : 1. Problem Identification; 2. Problem awareness; 3. Literature review; 4. Identification of artifacts and classes of problems; 5. Proposition of artifacts; 6. Design of the selected artifact; 7. Artifact development; 8. Artifact evaluation; 9. Clarification of achieved learnings; 10. Conclusions; and 11. Generalization for a class of problems. In Lacerda et al. (2013), the same authors present what seems an early version of their DSR proposition - a five phase organization consisting of "1. Awareness; 2. Suggestion; 3. Development; 4. Evaluation; and 5. Conclusion" (LACERDA et al., 2013, p. 750, our translation). For this study, the 12 original phases are clustered and organized in 5, but in a slightly different arrangement of the one shown in Lacerda et al.'s: **1. Problem and Context; 2. Related Artifacts; 3. Development; 4. Evaluation; and 5. Conclusion**. Instead of a Suggestion phase, all artifact development phases are resumed into one Development Phase. It also seemed relevant to maintain one phase to study the "Related Artifacts", which corresponds to Dresch, Lacerda and Antunes Jr.'s original phase 4. "Identification of artifacts and classes of problems" (2015). Table 4 details the arrangement; the methodological procedures; and the objectives.

Table 4 – Research phases, methodological procedures and objectives

Adapted Research Phases	Methodological Procedures	Objectives
1. PROBLEM AND CONTEXT	**1.a)** Systematic literature review (CONFORTO; AMARAL; SILVA, 2011) **1.b)** Narrative literature review (GREEN; JOHNSON; ADAMS, 2006; FERRARI, 2015)	
2. RELATED ARTIFACTS	Data treatment and analysis: **2.a)** Literature review analysis, organization into categories, and insight description; **2.b)** Semi-structured interviews (GRAY, 2004, protocol based on: Design Council (2007a; 2007b) and Camere and Karana (2018, p. 582) Data treatment and analysis: **2.c)** Interview transcription and analysis based on the adapted Mosaic Method (KIM; LEE, 2016), through a framework developed based on the PDP (ROZENFELD et al., 2016), the Double Diamond (DESIGN COUNCIL, 2007a; 2007b), and on the adapted Mosaic Method (KIM; LEE, 2016); **2.d)** Design process models elaboration by the framework developed based on the PDP, the Double Diamond, and the adapted Mosaic Method; **2.e)** Approval of final design process case studies and design process models by interviewees;	**O1-** To identify artifacts related to the representation and description of the biodesign process and biodesign teaching and learning; **O2-** To underline didactic biodesign process models based on interviews with experienced biodesign professionals;
3. DEVELOPMENT	**3.a)** Literature review insights from 2.a give basis to the framework's requirements; **3.b)** Framework's requirements from 3.a give basis to learning objectives (ERASMUS UNIVERSITY ROTTERDAM, 2023); **3.c)** Learning objectives from 3.b are the basis for the framework formulation, along with Sörensen`s work (2018); **3.d)** Framework elements detailing and materialities elaboration: project journal, grow-it-yourself kit; **3.e)** Development of a framework application script; **3.f)** Framework evaluation rubric elaboration;	**O3 –** To define the requirements for the teaching and learning facilitating artifact; **O4-** To formulate the framework for teaching and learning structure and elements; **O5-** To establish an evaluation rubric for the proposed framework and its outcomes;
4. EVALUATION	**4.a)** Application on the OD508 – Materials and Processes III course at the Federal University of Paraná; **4.b)** Overt observation (GRAY, 2004) **4.c)** Evaluation by the course professor through the Framework's Evaluation Rubric; **4.d)** Evaluation by the students through the framework's evaluation rubric; - Data treatment and analysis: **4.e)** Overt observation is related to the learning objectives; **4.f)** Evaluation by the course professor is tabulated; **4.g)** Evaluation by the students is tabulated and frequency is analyzed;	

Table continues next page

Table 4 – Research phases, methodological procedures and objectives

Adapted Research Phases	Methodological Procedures	Objectives
	4.h) Data is triangulated: (I) Overt observation, (II) Evaluation by the course professor; and (III) Evaluation by the students. **4.i)** Pattern matching with the learning objectives (GRAY, 2004); **4.j)** Immersion at the Cluster of Excellence Matters of Activity; **4.l)** Interview of MoA members; - Data treatment and analysis: **4.m)** Organization of interview answers in a text; **4.n)** Elaboration of framework's contingency heuristics and generalization for a class of problems	
5. CONCLUSION		

Source: Elaborated by the author (2023)

The next sections describe the research phases and methodological procedures as shown in Table 4.

3.2 PHASE 1 - PROBLEM AND CONTEXT

Figure 11 resumes the methodological procedures for phase 1, which addresses the problem and the context. A systematic literature review (**1.a**) is one of the recommended phases of the DSR. This methodological procedure supports the entire research, along with a narrative literature review (**1.b)**, laying the foundations for this thesis and contributing to the artifact`s development.

Figure 11 – Research phase 1 methodological procedures

Phase 1 – Problem and Context	Phase 2 – Related Artifacts	Phase 3 - Development	Phase 4 - Evaluation	Phase 5 - Conclusion

1.a) Systematic literature review (CONFORTO; AMARAL; SILVA, 2011)
1.b) Narrative literature review (GREEN; JOHNSON; ADAMS, 2006; FERRARI, 2015)

Source: Illustrated by the author (2021)

3.2.1 Systematic and narrative literature review

The systematic literature review strategy is adapted from Conforto, Amaral, and Silva's (2011) roadmap. The selected databases for this study are 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 is made and the search is performed considering the paper's title, abstract, and keywords.

In some cases, information on the design process is not the paper's central theme, and consequently, it is not explicit in the paper's title or abstract. Hence the filter application follows an open reading strategy, reading the whole paper when necessary. The exclusion criteria are:

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

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

(3) strict applications, such as to medical (engineered organs, tissues) and food industry;

(4) strict definition of living matter morphogenesis.

In addition to these filters the sample of papers included publications from two research laboratories that do research in biodesign: MIT Mediated Matter Lab and TUDelft Material Experience Lab. With this addition, the first sample of papers that is systematically analyzed for research gaps and emphasis is obtained.

To prevent some biases, such as search strings and even publication biases, a narrative review is also recommended (FERRARI, 2015). According to Ferrari, narrative threads could be lost in the strict rules of only systematic reviews. A narrative review "can address one or more questions and the selection criteria for inclusion of the papers may not be specified explicitly" (FERRARI, 2015, p.231). Following Ferrari's recommendation, a narrative review is developed. Papers and studies from workgroups and researchers that are mentioned by the authors retrieved in the systematic review are added. The dynamic is similar to snowball sampling (GRAY, 2004), where papers that fit the characteristics of inclusion criteria are added until a representative sample is achieved. Books are also included in the narrative literature review, as well as other references brought in biodesign symposiums and events attended by the author.

3.3 PHASE 2 - RELATED ARTIFACTS

This phase addresses objectives O1 and O2: O1- To identify artifacts related to the representation and description of the biodesign process and biodesign teaching and learning; and O2- To underline didactic biodesign process models based on interviews with experienced biodesign professionals. Figure 12 reviews the detailed procedures in phase 2.

Figure 12 – Research phase 2 methodological procedures

Phase 1 – Problem and Context	Phase 2 – Related Artifacts	Phase 3 - Development	Phase 4 - Evaluation	Phase 5 - Conclusion

Data treatment and analysis:
2.a) Literature review analysis, organization into categories, and insight description;

2.b) Semi-structured interviews (GRAY, 2004, protocol based on: Design Council (2007a; 2007b) and Camere and Karana (2018, p. 582)

Data treatment and analysis:
2.c) Interview transcription and analysis based on the adapted Mosaic Method (KIM; LEE, 2016), through a framework developed based on the PDP (ROZENFELD et al., 2016), the Double Diamond (DESIGN COUNCIL, 2007a; 2007b), and on the adapted Mosaic Method (KIM; LEE, 2016);
2.d) Design process models elaboration by the framework developed based on the PDP, the Double Diamond, and the adapted Mosaic Method;
2.e) Approval of final design process case studies and design process models by interviewees;

Source: Illustrated by the author (2021)

The systematic and narrative literature review procedures are also used to find artifacts related to the representation and description of the biodesign process and biodesign teaching and learning. Therefore, the work in this phase begins with the analysis of the literature review (**2.a**). In a table, every related artifact is numbered and categorized according to a structure: 1.1 Context; 2.1 Design with the living concepts; 2.2 Ethical implications; 2.3 Characteristics of biodesigned artifacts; 2.4 Intro. Design process; 2.5 Design process; and 2.6 Teaching and learning. Furthermore, insights triggered by each biodesign-related artifact are gathered in the same table.

In the next step, aiming to develop biodesign process models as case studies intended for the framework, semi-structured interviews are made (**2.b**):

3.3.1 Interview protocol

According to the Design Council's literature review, "case studies are often used to illustrate the process, demonstrating its clear relevance to business practice" (2007b, p.4). For this study, the decision was to build biodesign representations based on real cases.

Interviews are recommended by Dresch, Lacerda, and Antunes Jr. as they are "an opportunity to gather information that is not normally found in bibliographic sources" (2015, p. 31). Gray considers semi-structured interviews "the most effective method for asking open questions and for eliciting more detailed responses [… they] allow for the use of probing questions in response to unclear or incomplete answers" (2004, p. 111). Thus, the semi-structured approach is chosen for interviewing designers.

The sampling strategy would be quota sampling, where subjects are non-randomly selected from an identified strata "until the planned number of subjects is reached" (GRAY, 2004, p. 88). In this study, **six designers are interviewed, they have worked with living materials for at least one year**. **They were engaged in a product development that had at least one full prototype approved for the Deliver/Detailed Project stage.** Designers are first invited based on a web search for Brazilian biodesign initiatives (projects, companies, experimentations), and the invitation is extended to foreign initiatives until the desired sample is complete. The initial contact is made by email – the addresses are public emails on the initiative's web pages. If there is a response of interest, the interview dates are scheduled according to the availability of the participants. A link for the interview meeting is sent - the platform is UFPR`s institutional platform Microsoft Teams. To make the interviewees more comfortable, the script is made available in advance, along with the Key Information and Consent Form and the Request for Use of Image and/or Voice for Research. The participants are asked to choose a project that they could share information about, a case study. Participants are also asked to prepare a graphic representation of the design process.

The questionnaire that structures the interviews is presented in Appendix 2. Questions are organized by personal information, project overview, and design process, according to the Double Diamond's (DESIGN COUNCIL, 2007a; 2007b) macro phases and activities. Two key references for elaborating the interview structure are Camere and Karana's script (2018, p.582), which is reproduced in Appendix 1, as well as the Design Council's study (2007a; 2007b). The interview time is estimated at a maximum of 1 hour, but not controlled. The same researcher performs the procedure to reduce the "interviewer effect" (GRAY, 2004). Transcription follows **(2.c)** and answers are organized according to the design process analysis framework (described in the next sections). From the organized interviews, a text is written and sent for approval for the interviewees (**2.e**).

In this stage, the models, which are support artifacts, are one of the outputs (2.d). They are developed through a framework formulated based on the Double Diamond (DESIGN COUNCIL, 2007a; DESIGN COUNCIL, 2007b), the PDP (ROZENFELD et al., 2016), and the Mosaic Method (KIM; LEE, 2017). The idea is to draw didactic comparisons of these

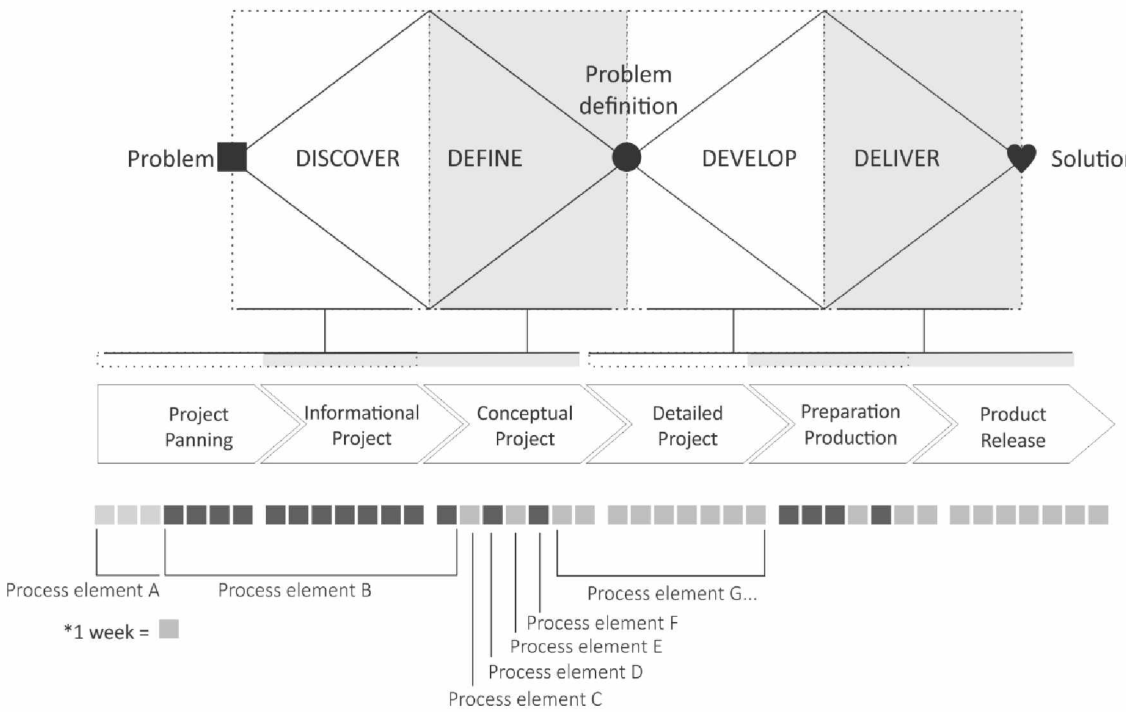
established models with the biodesign process, so students can understand it better based on what they already know.

3.3.2 Design process analysis framework - Double Diamond, PDP, and the Mosaic Method

To draw the design process models a design process analysis framework is formulated. A parallel is drawn among the three studies adopted as main reference: the first one is the Design Council's "Eleven Lessons in Design: A study of the design process" (DESIGN COUNCIL, 2007a), this study relied on the Double Diamond framework. The second study is Rozenfeld et al.'s (2006) Product Development Process (PDP) from the book: "*Gestão de desenvolvimento de produtos: uma referência para a melhoria do processo*" (Managing product development: a reference for process improvement, our translation). The third study is an adaptation of Kim and Lee's (2017) Mosaic Method. The whole background of the three studies is described in detail in Appendix 8.

Figure 13 illustrates the Mosaic method strategy adapted to fit the Double Diamond and the PDP models.

Figure 13 – Example of a representation of the Mosaic method in the framework



Source: Illustrated by the author (2021), according to the Design Council (2007 a; 2007b), Rozenfeld (2016) and Kim and Lee (2017)

The process models are sent to the interviewees for necessary changes and approval (**2.e**).

3.4 PHASE 3 - DEVELOPMENT

This phase involves the creative process of designing the artifact (framework) based on previously gathered information. Figure 14 provides an overview of the specific procedures for this stage.

Figure 14 – Research phase 3 methodological procedures

Phase 1 – Problem and Context	Phase 2 – Related Artifacts	Phase 3 - Development	Phase 4 - Evaluation	Phase 5 - Conclusion
		3.a) Literature review insights from 2.a give basis to the framework's requirements; **3.b)** Framework's requirements from 3.a give basis to learning objectives (ERASMUS UNIVERSITY ROTTERDAM, 2023); **3.c)** Learning objectives from 3.b are the basis for the framework formulation, along with Sörensen`s work (2018); **3.d)** Framework elements detailing and materialities elaboration: project journal, grow-it-yourself kit; **3.e)** Development of a framework application script; **3.f)** Framework evaluation rubric elaboration;		

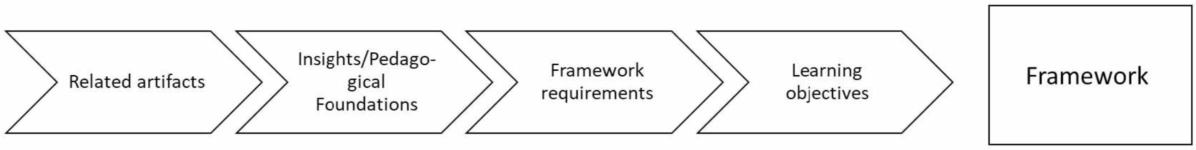
Source: Illustrated by the author (2021)

One important reference for the framework's development is the work of Sörensen: "A Material Framework for Product Design: The Development of Reflective Material Practices", from 2018. The pedagogical foundations to develop the framework are lent from this work. Principles like: Experiential learning theory (theory of experience, or learning-by-doing: activity-oriented); Meta-cognition (reflection, complex and open assignments); Designing for learning; Bloom's Taxonomy; Reflection-in-action, or intuitive expertise; knowing-in-action with Methods (can act as a framework, or frames for reflection, negotiation and action in a design process); Framing and reframing (SÖRENSEN, 2018) – guide the process of developing framework.

The development drew on the insights gathered on the literature review. The Frameworks' requirements are underlined based on the insights and Sörensen's pedagogical foundations **(3.a)**. For each requirement or set of requirements, a learning objective is elaborated according to the Bloom Taxonomy **(3.b)** – the formulation of the objectives is guided by the course "Assessment in Higher Education: Professional Development for Teachers" provided by the Erasmus University Rotterdam (2023).

The creative process of designing the framework is based on the learning objectives and considers the students` and teachers' context, materialities to be used, and activities (**3.c and 3.d**). Figure 15 shows the flow of the framework development.

Figure 15 – Framework development flow



Source: Illustrated by the author (2023)

In addition to the framework, a Framework Evaluation Rubric is designed (**3.f**). This rubric is meant for the subsequent phase of Evaluation. The rubric is based on the description of the activities and the learning objectives – aiming to inquire students and the course professor about their perception about the framework.

In this stage, the framework artifact is designed, as well as an evaluation rubric for the proposed framework, fulfilling objectives O3 – To define the requirements for the teaching and learning facilitating artifact; O4- To formulate the framework for teaching and learning structure and elements; and O5- To establish an evaluation rubric for the proposed framework and its outcomes.

3.5 PHASE 4 - EVALUATION

The framework's **instantiation** is performed in the Design Department's Product Design undergraduate program of the Federal University of Paraná (UFPR). It takes place in the mandatory course "*Materiais e Processos III*" (Materials and Processes III, our translation) in 2022 (**4.a**). Figure 16 shows the detailed procedures for phase 4.

Figure 16 – Research phase 4 methodological procedures

Phase 1 – Problem and Context	Phase 2 – Related Artifacts	Phase 3 - Development	Phase 4 - Evaluation	Phase 5 - Conclusion
			4.a) Application on the OD508 – Materials and Processes III course at the Federal University of Paraná; **4.b)** Overt observation (GRAY, 2004) **4.c)** Evaluation by the course professor through the Framework's Evaluation Rubric; **4.d)** Evaluation by the students through the framework's evaluation rubric; - Data treatment and analysis: **4.e)** Overt observation is related to the learning objectives; **4.f)** Evaluation by the course professor is tabulated; **4.g)** Evaluation by the students is tabulated and frequency is analyzed; **4.h)** Data is triangulated: (I) Overt observation, (II) Evaluation by the course professor; and (III) Evaluation by the students. **4.i)** Pattern matching with the learning objectives (GRAY, 2004); **4.j)** Immersion at the Cluster of Excellence Matters of Activity; **4.l)** Interview of MoA members; - Data treatment and analysis: **4.m)** Organization of interview answers in a text; **4.n)** Elaboration of framework's contingency heuristics and generalization for a class of problems	

Source: Illustrated by the author (2021)

The framework's evaluation in the course takes six presential meetings of three hours each, along with activities for students to do at their homes. Although the course is mandatory for the students, their participation in the present research is optional: data from students who do not wish to take part in the study are not collected. The Informed Consent Form and Request for Use of Image and/or Voice Sound for Research Form are made available in advance for an informed decision students are presented with contents, repertoire, and reflections, according to the framework's application script. They are guided in activities and develop a project of a biodesign product**.** The project may be developed in teams of two to four people. The framework foresees the use of a grow-it-yourself mycelium kit, which is developed with NeoMatter[12] startup. Also, it foresees a structured project journal which is provided for them. For ethical purposes students are not graded for their participation, only feedback is provided. The participating students receive a code in order to preserve their identities.

To assess the project's developed by the students, an evaluation rubric for the project is proposed along with the artifact development phase. It considers the project's feasibility and process comprehension, concept quality, form-giving, product market placement, time management, and presentation quality. Each group is anonymously evaluated by this researcher, the teacher of the mandatory course, a graduating student of the Biotechnology course, and the CEO of NeoMatter.

During the framework's application, the overt observation procedure is structured according to the learning objectives (**4.b**). This procedure allows some level of participation by the researcher and students are aware that the observation is happening (GRAY, 2004, p. 239).

The framework is also evaluated by the course professor (**4.c**) and by the students (4.d) at the end of the project following the evaluation rubric designed in 3.b.

Data treatment involves the tabulation of the overt observation concerning the learning objectives **(4.e)**, the evaluation by the students and course professor is also tabulated, and frequency distribution of the answers is analyzed **(4.f and 4.g)**. As Gray writes that: "for most qualitative approaches, reliability is improved, if not guaranteed, by **triangulation**, gathering information, for example, from multiple sources or by using multiple data gathering tools" (2004, p.344) - the analysis is based on triangulation of the (1) overt observation data, the (2) student's perception through the evaluation rubric and the (3) course professor's perception through the framework's evaluation rubric **(4.h)**. Results are compared to the expected artifact learning objectives. Gray refers to this process as **pattern matching** (GRAY, 2004) **(4.i)**.

A fourth evaluation step is included: (4) insights from the Cluster of Excellence »Matters of Activity. Image, Space, Material« at the Humboldt University in Berlin. Matters of Activity is a different constellation in which innovative biodesign research and biodesign

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[12] LINKEDIN. Luiz Eduardo Piá de Andrade's profile. Available at: https://www.linkedin.com/in/luiz-eduardo-pia/. Accessed on: January 24, 2023.

teaching and learning happen. An **immersion** in the context of the experienced, interdisciplinary cluster was made during six month sandwich period and the experiences are used to discuss the framework's results **(4.j)**. In the immersion process, two members of the cluster are interviewed and provided in-depth feedback about the framework **(4.l)**. They also digitally sign a key information consent form for participating in the research. The interviews are summarized into a text **(4.m).**

Finally, contingency heuristics for the framework are summarized – making its limitations explicit and providing context-related recommendations **(4.n)**.

4 RESULTS AND ANALYSIS - LESSONS FROM THE BIODESIGN PROCESS

This chapter presents the results. Figure 17 shows the chapter overview.

Figure 17 – Lessons on the biodesign process chapter overview

Chapter overview

1. Introduction | 2. Design with the living concepts, and practice | 3. Methodological strategy and procedures | 4. Lessons on the biodesign process | 5. Discussion | 6. Conclusion | Appendix

4.1 Problem and context
4.2 Lessons from biodesign-related artifacts
4.3 Lessons from designers
  4.3.1 Pilot
  4.3.2 Design process in collaboration with mushrooms
  4.3.3 Design process in collaboration with plants: trees
  4.3.4 Design process in collaboration with plants: grass
  4.3.5 Design process in collaboration with bacteria
4.4 The framework
  4.4.1 Pedagogical foundations
  4.4.2 Framework requirements
  4.4.3 Learning objectives
  4.4.4 Framework for teaching and learning design in collaboration with other living organisms
  4.4.5 Framework evaluation rubric
4.5 Experiences in biodesign teaching and learning
  4.5.1 Project results and evaluation
  4.5.2 Overt observation
  4.5.3 Framework evaluation by students
  4.5.4 Framework evaluation by the course professor
  4.5.5 Triangulation and pattern matching
  4.5.7 Framework`s contingency heuristics and generalization to a class of problems

Source: Illustrated by the author (2023)

The next section brings Phase 1 – Problem and Context results.

4.1 PROBLEM AND CONTEXT

The Phase 1- Problem and Context began with a systematic literature review followed by a narrative literature review. The review was initiated in May 2020 and was completed with new research strings in September 2020 and November 2020. The two consulted databases rendered a total of 1347 results through the research strings. The exclusion criteria filtered 43 relevant results, of which 4 could not be accessed, hence 39 papers. Meanwhile, through the narrative literature review, 9 papers were added from MIT Mediated Matter Lab and TUDelft

Material Experience Lab. These results compose what was considered an initial sample of 48 papers, which were analyzed for research gaps and emphasis. Appendix 3 presents a table with all the analyzed references and concepts that could be highlighted in them.

Later on, books and other references brought in biodesign symposiums and events this author attended were included.

Chapter 2 presents a compilation of relevant topics and emphasis found in the literature review, they lay the theoretical background for this investigation.

4.2 LESSONS FROM BIODESIGN-RELATED ARTIFACTS

This section is dedicated to fulfilling specific objective O1- To identify artifacts related to the representation and description of the biodesign process and biodesign teaching and learning. The artifacts here consist of each piece of recommendation, concept, advice, method, model, or framework related to the biodesign process or to biodesign teaching and learning. Table 5 organizes the information. For each approach or recommendation, categories and labels are established: 1.1 Context; 2.1 Design with the living concepts; 2.2 Ethical implications; 2.3 Characteristics of biodesigned artifacts; 2.4 Introduction to the design process; 2.5 Design process; and 2.6 Teaching and learning. Moreover, insights prompted by those artifacts are listed and numbered, aiming at the design of the framework.

Table 5 – Artifact analysis and insights

	Category	Author	Artifact, recommendation, advice	Insight
1	1.1 Context 2.1 Design with the living concepts / Design process	HBBE (2021); Vettier (2019)	Biodesign aims to include other life forms in our day-by-day;	Ethical reflection on a probiotic built environment;
2	2.1 Design with the living concepts / Design process	Pasold (2020); Dew and Rosner (2018); Oxman et al. (2015); Oxman (2015)	Templating, physical or immaterial frameworks to inform bottom-up processes of material disposition and composition in top-down design approaches. System's patterns. Patterns that reflect change;	To reflect on what would mean templating in the project: is it light? Humidity? Air? How do you template air, humidity, and light? How to creatively guide these patterns?
3	2.1 Design with the living concepts/ 2.3 Characteristics of biodesigned artifacts/ 2.5 Design process	Camere and Karana (2018); Karana et al. (2018); Myers (2018); Keune (2017)	"Legible formal language"; a "new vocabulary to the language of form"; Aesthetical and experiential qualities;	Aesthetical reflection – what would be this new formal language? Helped by MA2E4 toolkit;
4	2.2 Ethical implications 2.5 Design process	Biodesign Challenge (2022); UWA (2022); The University of Sidney (2022); UAL (2022); Grushkin (2021); Collet (2020); Mancuso (2019); Myers (2018); Dew and Rosner (2018); Pinto and Pugliese (2017)	Ethical considerations about the organism; agency and spontaneous developments; Considering the other organisms as users; Characteristics to read: legible textures, defensive traces, reparative expressions, vital decay, and performative scarcity (DEW; ROSNER, 2018); Designing for material recuperation; Collaborating with more-than-human actors & timescales; approaching material properties as prototyping sites (DEW; ROSNER, 2018);	Organism Design Empathy Map; Heather Barnett's "Small acts of being" (2020); Reflective sensibility to read the other organism. How does it express itself? Reflective sensibility to sense the organism's timescale and dimensions. Feel it like another "person", unname it as fungi, and rename it as someone;
5	2.2 Ethic al implications	Cho (2018); Myers (2018); Ginsberg et al. (2014)	Manage organism/process ownership;	Partnership with the University's innovation agency and legal department;

Table continues next page

Table 5 – Artifact analysis and insights

	Category	Author	Artifact, recommendation, advice	Insight
6	2.3 Characteristics of biodesigned artifacts and materials	Camere and Karana (2018)	Special abilities of the organism; "Grow-ability" manufacturing opportunities;	What are the organism's talents?
7	2.3 Characteristics of biodesigned artifacts and materials / 2.4 Intro. design process	Zolotovsky (2012) Camere and Karana (2018)	Concurrent production of material and product;	Production planning – material and product;
8	2.4 Intro. design process	Collet (2013; 2017; 2020) Camere and Karana (2017; 2018) Myers (2018)	Project identification according to biodesign frameworks;	Presenting the biodesign frameworks with examples to form repertoire;
9	2.4 Intro. design process	Pasold (2020); Kera (2014)	Online communities share knowledge and open-source resources and collaborate developing protocols, tools, and ethical discussion	To begin an online open-source page, accounting students experiences; final project deliverable in a DIY step-by-step format;
10	2.5 Design process	Diniz (MAAT, 2021); Diniz (2020b); Neeves (2018) Dade-Robertson (2021); Antinori et al., 2020); Niyazbekova; Nagmetova; Kurmanbayev, (2018); Myers (2018)	Thinking accross scales for modularity – like a knitting yarn pattern or mycelium assemblable modules; using "scaling analysis" and "non-dimensional numbers" (NEEVES, 208); "So modularity is kind of the way we scale up the prototypes" (DINIZ, 2020b); Micro and nanoscales; across scales; Biological assembly is simultaneous at multiple scales;	To conduct in-class brainstormings focused on modularity and cross-scale thought;
11	2.5 Design process	Dade-Robertson (2021); Pasold (2020); Abreu (2019); Cho (2018);	Collaboration with other scientists;	Briefing and contract sheets and checklists; "[...]our initial aim was to learn how to effectively communicate accross disciplinary boundaries. We shared in joint studio reviews, weekly lab

Table continues next page

Table 5 – Artifact analysis and insights

	Category	Author	Artifact, recommendation, advice	Insight
		Camere and Karana (2018); Sabin and Jones (2018)		meetings, invitations to seminars and conferences, and informal gatherings." (SABIN; JONES, 2018, p. 48). Later Sabin and Jones released a joint elective graduate course and paired students of different backgrounds to work together in projects at the LabStudio.
12	2.5 Design process	UAL (2022); Grushkin (2021); Sabin (2021); Diniz (2020b); Pasold (2020); Bianchini and Quinz (2019); Sabin and Jones (2018); Pinto and Pugliese (2017)	Systematic entanglement of the living and non-living, to think of a system; To think about systems; systemic design; characterisations of complexity cited by Pasold (2020): the system's unpredictability, context dependency, noise, emergence, stochasticity, non-linearity, crosstalk, open systems, overlapping hierarchies, incomplete understanding and possible multiple characterizations. To define system's boundaries; to also design the environment;	How does the system work and how to maintain it? Drawing a system to what would be the business of the project developed. To list all variables.
13	2.5 Design process	Dade-Robertson (2021) Collet (2020) Myers (2018, p. 269)	Traditional craft forms from agriculture, brewing, baking and gardening;	Getting student's used to production processes;
14	2.5 Design process	UAL (2022); UCL (2022); Sabin (2021); Pasold (2020); Zhou et al. (2020); Kirdök et al. (2019); Dew and Rosner (2018);	Representation issues; simulation; Physical and digital equivalence in representation, Maxel, Voxel; CAD tools; Generative software; Use of Rhinoceros+Grasshopper; Kanguroo tools simulation; 3D Printing; Biocomputation; How do we represent change? Energy? Experience?	Reflection on representation tools and possibilities, mockup possibilities; Introducction to Rhinoceros+Grasshopper plugin;

Table continues next page

Table 5 – Artifact analysis and insights

	Category	Author	Artifact, recommendation, advice	Insight
		Sabin and Jones (2018); Oxman (2010)	“[...] including how to generate complex morphological systems and simulate growth protocols that can be applied to nature. Students work with advanced software for animation and simulation and develop basic programming skills” (UCL, 2022); “software packages which are not usually available for designers”– “we introduce microscopy, biochemistry notions, we observe living systems in different kinds of scales – but we also see these as a new representation of biological phenomena, as a new way of drawing [...] it is essentially a new way of communication and representation in design, in a design discipline ” (DINIZ, 2020a); GenerativeComponents [GC] by Bentleyyt, RhinoScript (SABIN; JONES, 2018);	
15	2.5 Design process	Yang, Gao, and Xu (2020); Dew and Rosner (2018); Li et al. (2017); Keune (2017)	Four-dimensional thinking. Designing performativity, the change over time; “temporal potentials”; interaction potentials, considering the material’s agency; scripts instead of properties; change in size, form, and/or functionality through time;	How to help students think in four dimensions? Maybe a design timeline;
16	2.5 Design Process	Brayer (2019); Bianchini, and Quinz (2019); Vettier (2019); Keune (2017); Liu et al. (2017)	Life cycle: birth, growth, maintenance, control, end. Seasons. Diachronic properties of the materials;	To help students to think about diachronic properties of the materials;
17	2.5 Design process	Barnett (2020); Dew and Rosner(2018) Collet (2017; 2020)	Give some control to the organism’s spontaneity; The organism is active in the design process;	To live some space in class activities for the students to interact with the organism’s spontaneity;

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Table 5 – Artifact analysis and insights

Category		**Author**	**Artifact, recommendation, advice**	**Insight**
		Myers (2018)		
18	2.5 Design process	Abreu (2019)	MBI method is structured in small interchangeable modules; a combination of methods from different areas; non-linear; The method presents a “momentum cell” a stage to summarize knowledge, create and revise ideas, and make decisions, similar to a “define” stage; The other two momentums are the “Momentum Rep”, which refers to microorganism selection and all sorts of information gathering, such as sensorial factors, cultural transversal factors, the organism’s fisioloy and ecology - and “Momentum Morf”, which refers to everything related to the idea’s implementation, discussion and results analysis . All momentums are represented by hexagons (except momentum cell), which can be arranged according to the projects necessity;	This relates to SCRUM iterations and interactions, which are recommended in new design case-scenarios, with high levels of uncertainty where work is exploratory, high complexity, high risk and great change rates (PMI; AGILE ALLIANCE, 2017) “[...] operate within dynamic loops of feedback, reciprocity, and generative fabrication.” (SABIN, 2018b, p.271)
19	2.5 Design process	Pasold (2020) Abreu (2019)	Abreu also reinforces the importance of the project manager’s role to articulate and motivate contribution from all participants. Coordination: “[...] checking in and following along the same plan [...]especially in light of the aforementioned difficulty of planning out an accurate project timeline within the context of working with living matter” (PASOLD, 2020, p. 151);	To develop the project’s predictive timeline and to estimate the equipment and budget;
20	2.5 Design process	Abreu (2019)	Database reference for beginners;	To offer a repertoire for beginners with information about the organism, like Royal Botanic Gardens’ “Kew State of the World’s Fungi” (2018) and papers. To indicate where to acquire some

Table continues next page

Table 5 – Artifact analysis and insights

	Category	Author	Artifact, recommendation, advice	Insight
				species locally, like "Fungicultura" (2022);
21	2.5 Design process	Dade-Robertson (2021)	Technology Readiness Level (TRL)	To introduce the TLR scale in class;
22	2.5 Design process	Camere and Karana (2018);	Form-giving and plastic research programmation and mediation;	To previously do some experiments with form to understand how shape affects growth to provide a starting point for students to do their own experiments;
23	2.5 Design process	Sabin and Jones (2018)	"[...] design processes rooted in experimentation without predetermination of form. Emphasis is placed upon the dynamics of natural systems in context, of behavior and process in the material formation of difference and heterogeneous entities." (SABIN; JONES, 2018. p.363)	To make room in the course for some free experimentation;
24	2.5 Design process/ 2.6 Teaching and learning	UAL (2022); Pasold (2020);	One initial understanding phase, a more application-focused phase and an implementation/scaling phase – in which the project is in reality communicated and reported, submitted to critique;	It seems those phases could be treated as three different projects – (1) one to understand the material, its possibilities and a possible problem to be tackled; (2) another to narrow down and direct the project and experimentation to a solution, and finally; (3) the study for market implementation of the solution;
25	2.5 Design process/ 2.6 Teaching and learning	The University of Sidney (2022); UAL (2022); Abreu (2019); Cho (2018); Camere and Karana (2018); Sorensen (2018)	Scientific literacy; Acquiring vocabulary and lexicon for credibility; a shared lexicon and glossary;	Acquiring scientific literacy through reading scientific papers, through a glossary, and through theory classes;

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Table 5 – Artifact analysis and insights

	Category	Author	Artifact, recommendation, advice	Insight
26	2.5 Design process/ 2.6 Teaching and learning	Pasold (2020); Karana et al., (2018); Sorensen (2018); Parisi, Rognoli and Ayala-Garcia, (2016)	Material Driven Design (MDD); a materials experience vision; materials experience patterns; categorization studies;	To help students to get acquainted to the experiential dimensions of the new material they are collaborating with;
27	2.5 Design process/ 2.6 Teaching and learning	Pasold (2020); Collet (2020); Pasold (2020); Karana et al., (2018); Sorensen (2018); Karana et al. (2018); Sabin and Jones (2018); Parisi, Rognoli and Ayala-Garcia, (2016);	Material first; a beginning phase to understand the material; Systematically prototyping, material tinkering - in the beginning of the project, experimentation with the organism's growth. Designers also develop manufacturing. Nature's model of trial and error; experiential learning; learning by doing;	To make space and provide resources for students to do some tinkering; To provide material samples for students to perform tests in; To provide opportunity for manufacturing process tinkering; To make space for students to have the opportunity to do experimentation;
28	2.5 Design process/ 2.6 Teaching and learning	Karana et al., (2018)	More than demonstrators and surrogates, an adequate application?	Follow MDD's to build a material design vision;
29	2.5 Design process/ 2.6 Teaching and learning	Pasold (2020); Abreu (2019); Karana et al. (2018) Camere and Karana (2018); Sorensen (2018); Collet (2017, p.34); Parisi and Rognoli (2017);	Project documentation, diary; a record book; lab journal; design catalogs; sketches and photographs; Soft control systems (such as in bread making); grow-made protocols; structured process for experimentation, according to variables and themes; designerly skills of visualizing content;	To adapt Charlotte Sorensen's monitor pack (SORENSEN; THYNI, 202); To develop a helpful template for project journaling; To structure a lab journal to support students in their experiments and in their course project;
30	2.5 Design process/ 2.6 Teaching and learning	Pasold (2020); Karana et al. (2018)	Consulting specialists to speculate possible outcomes;	To invite specialists over in some classes;
31	2.6 Teaching and learning	Dade-Robertson (2021); Sabin and Jones (2018);	Maybe there is no need for the designer to know everything about biological processes. The author procedes to imagine an alien species. Looking to earth these alien beeings	Reflection on the glassblower and the alien bookshelf examples;

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Table 5 – Artifact analysis and insights

	Category	Author	Artifact, recommendation, advice	Insight
			would not understand the difference between human being agents and the flatpack bookcases. “What they observe from their spacecraft is an ongoing process of self-assembly. Interactions of different elements of matter produce bookcases spontaneously. For some reason, flatpack bookcases are very useful for our alien species, but they don’t possess the necessary knowledge to understand how to produce them [...]. Instead they want to intervene to allow this spontaneous process to happen but to alter the outcomes such that the resulting furniture matches their specifications” (DADE-ROBERTSON, 2021a, p.33). The aliens could try a numbera number of interventions: in changing the assembly information, for example, the bookcases would still happen autonomously “outside their direct control”; “[...] The vitality of this research depends upon a collective intuition, or knowing where to look, along the way. This clarity comes forth from doing, making, collaborating, and failing. “Knowing where to look” requires a constant refinement of one’s intuition. There are no fields within this space of refinement; rather, it undulates within a multi-set of honed intuitions [...]” (SABIN; JONES, 2018, p. 52).	
32	2.6 Teaching and learning	Abreu (2019)	Microorganism catalogcards, which mix biological, aesthetic and sensory information;	To use Abreu’s catalog cards;
33	2.6 Teaching and learning	Sorensen (2018)	Material Framework for Product Design	Experiential characterization map from MA2E4 Toolkit (CAMERE; KARANA, 2018b); to work with

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Table 5 – Artifact analysis and insights

	Category	Author	Artifact, recommendation, advice	Insight
				Sörensen's educational foundations;
34	2.6 Teaching and learning	Pasold (2020); Sorensen (2018)	Do-it-yourself, cook-it-yourself or grow-it-yourself initiatives;	To provide students with a grow-it-yourself kit;
35	2.6 Teaching and learning	Turano et al. (2020)	Biodiseño en Colegios;	To develop a complete facilitation method organized into a book; and following the UN's Sustainable Development Goals;
36	2.6 Teaching and learning	Pasold (2020); Sabin (2021); Sabin and Jones (2018); Pinto and Pugliese (2017)	A well defined design space; controlling complexity; making things more concrete; reducing parameters and constraints; "reduction to certain conditions that are explored individually first to establish certain patterns, learning through designing and making experimentation integral to the process of designing or constructing the system, which is modelled on nature's trial and error way [...]" (PASOLD, 2020, p.138);	Thinking about ways to simplify the variables – like with a grow-it-yourself kit; Providing a journal to help students to control and assess the variables;
37	2.6 Teaching and Learning	Abreu (2019) Liu et al. (2017)	Concerns with biosafety;	To discuss risk assessment;
38	2.6 Teaching and Learning	Abreu (2019)	Problems that might arise: not being able to grow the organisms correctly; not having access to adequate equipment, laboratorial infrastructure, and necessary supplies to grow the organisms; not to obtain the expected results even in predictable settings;	Risk assessment, planning ahead resources and a timeline, estimating reworking cycles, considering the literature to estimate growth;
39	2.6 Teaching and Learning	The University of Endinburgh (2022); UAL (2022); UCL (2022); Pasold (2020); Sabin (2018b); Sorensen (2018)	"[...]formal input in form of lectures and tutorials is not excluded from the syllabus and is in fact seen as a way of building a base level of understanding[...]"(PASOLD, 2022 p. 141). To enable students for theoretical backgrounding their projects and to discuss ethical perspectives.	To create a comprehensive repertoire of biodesign concepts and ethical reflexions;

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Table 5 – Artifact analysis and insights

	Category	Author	Artifact, recommendation, advice	Insight
			UCL has a "Literature Review" module; Sabin and Jones provided the students with specific biological concepts, such as vascular networking within the lung – so they could build from it	
40	2.6 Teaching and Learning	UAL (2022); Pasold (2020) Sorensen (2018) Pinto and Pugliese (2017)	Experiential learning; hands-on; learning by doing; Research-driven learning/curriculum;	To develop a class project with enough openness so students can develop questions and be proactive in project's inputs;
41	2.6 Teaching and Learning	The University of Sidney (2022); UAL(2022) UCL (2022) Pasold (2020) Abreu (2019) Sabin and Jones (2018) Sorensen (2018)	Combining Lab and Studio (and workshop) Infrastructure; Learning space – partners for feedback and exchange;	To adapt exercises to be done in the student's homes, so they can minimally have a laboratory experience; To develop in-class projects so students can minimally have a studio experience;
42	2.6 Teaching and Learning	UAL (2022); Pasold (2020) Sorensen (2018) Pinto and Pugliese (2017)	Explorations of existing biodesign strategies; teaching with examples rather than theory (SORENSEN; 2018);	Forming a repertoire of biodesign examples, presenting them in class. Presenting the design process models;
43	2.6 Teaching and Learning	Pasold (2020) Sorensen (2018) Pinto and Pugliese (2017)	Field trips;	To arrange a field trip to a lab or to the local companies which work with biodesign;
44	2.6 Teaching and Learning	UAL (2022); UCL (2022); Pasold (2020); The University of Sidney (2022); Sorensen (2018)	External feedback, criticism, peer review;	A peer-review structure to stimulate discussion;

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Table 5 – Artifact analysis and insights

	Category	Author	Artifact, recommendation, advice	Insight
		Sabin and Jones (2018) Universidad de Los Andes (2021)		
45	2.6 Teaching and Learning	Utrecht University (2022); UWA (2022); UAL (2022); UCL (2022); Pasold (20220)	Laboratory practice; "Introduction to Scientific Methods, Laboratory and Environmental Practices" Module;	To develop a partnership to get access to laboratory practice, to adapt some laboratory practices for students to do them in their homes;
46	2.6 Teaching and Learning	UAL (2022)	Learning outcome: Study and integrate the principles of biomimicry, in relation to designing structures, materials, behaviors, and/or intelligent systems;	To blend-in biomimicry content into the repertoire, to bring in biomimicry principles in the ethical foundations;
47	2.6 Teaching and Learning	UAL (2022)	Explore biological sciences and biofabrication tools and methods to study, transform, control and/or collaborate with living organisms;	To look for exploratory tools, maybe in collaboration with the Biotechnology department;
48	2.6 Teaching and Learning	UAL (2022)	Develop an original and complex biodesign portfolio of work;	To guide the classroom activities in a way that they could be portfolio-oriented, like a project;
49	2.6 Teaching and Learning	Biodesign Challenge (2022); The University of Endinburgh (2022); UAL (2022) Universidad de los Andes (2021)	Theoretical, global cultural, and socio-environmental contexts will inform the development of your personal biodesign agenda." (UAL, 2022, p. 7); UN sustainable development goals-driven projects;	Problem first instead of material first?
50	2.6 Teaching and Learning	The University of Endinburgh (2022); The University of Sidney (2022); Biodesign Challenge (2022)	Challenges and competitions;	There should be other ways to encourage students;

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Table 5 – Artifact analysis and insights

	Category	Author	Artifact, recommendation, advice	Insight
51	2.6 Teaching and Learning	Pinto and Pugliese (2017)	Students develop case-studies;	One might ask: if you would have to repeat case study x, what would be your step-by-step?
52	2.6 Teaching and Learning	UCL (2022)	"[...] through a series of short design projects, engaging individually and in groups with new research agendas [...]";	To develop small speculative 4-week projects;
53	2.6 Teaching and Learning	The University of Endinburgh (2022); The University of Sidney (2022); Sabin (2021); Sabin and Jones (2018)	Interdisciplinary project wih a major industry partner, an academic lead, working in teams with students from other disciplinary backgrounds;	To develop a partnership with professors of other disciplines to create opportunities for students to work in interdisciplinary teams;
54	2.6 Teaching and Learning	ASU (2022)	Research rotations: "During the first year of study, students will rotate between three laboratories. [...]All students will decide on a lab for the Ph.D. studies at the conclusion of the first year of study" (ASU, 2022);	To simulate a lab rotation creating different projects during the course in wich students can participate in different moments, rotating through projects;
55	2.6 Teaching and Learning	University of Endinburgh (2022); Utrecht University (2022)	Business-oriented projects, value creation-oriented, and innovation;	Give special attention to product market placement; exercising strategic reflection for biodesign;
56	2.6 Teaching and Learning	UAL (2022); Diniz (2020a); Barnett (2020); Pinto and Pugliese (2017)	"when working with living systems it is important to observe and learn from the organism. You cannot impose your will upon another life form to get it to perform for you, to fulfill your creative aspirations. You need to work with it, to try to understand its needs, to speculate on how it understands its surroundings" (BARNETT, 2020); "[...] students were assisted in identifying and understanding morphological, physiological and behavioural characteristics that influence a specific living	To imersively build empathy with the organism the students will be working with;

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Table 5 – Artifact analysis and insights

	Category	Author	Artifact, recommendation, advice	Insight
			actuator (single individual or a superorganism) that has impact on form giving/manipulation of the system, in a distinguishable way and that can be furthermore manipulated." (PINTO; PUGLIESE, 2017, p.1);	
57	2.6 Teaching and Learning	Diniz (2020b)	Living Systems Lab Design process: 1.Material selection; Material Manipulation 2.Living system selection; 3.Sterelization; Modularity; Innoculation; Incubation; Colonization; Termination; Stabilization: Living or Non Living;	To add this method in the repertoire;
58	2.6 Teaching and Learning	Sabin and Jones (2018)	Sabin and Jones list a number of questions that could work as design requirements for a living system: (SABIN; JONES, 2018, pp. 47-8);	To present the design requirements to the students in the course repertoire or even to brief a project with those design requirements;
59	2.6 Teaching and Learning	Biodesign challenge (2022) Universidad de los Andes (2021)	The Biodesign Challege evaluation rubric considers originality, feasibility, human impact, sustainability and risks	To consider the biodesign challenge rubric in assessing student's works

Source: Elaborated by the author (2023)

The next section presents the didactic biodesign process models based on the interviews.

4.3 LESSONS FROM DESIGNERS

In this section objective O2 is addressed - to underline didactic biodesign process models based on interviews with experienced biodesign professionals. First, the pilot study is described; followed by an explanation of the changes made in the interview protocol and data treatment; and then the results from the interviews with designers who work in collaboration with other living organisms are presented. Design process models in collaboration with mushrooms; with plants – trees; with plants – grass; and with bacteria are organized showing the categories of the phases: Discover, Define, Develop and Deliver; and Project Planning, Informational, Conceptual, Detailed Project and Preparation for Production.

After the pilot invitations were sent by email to 15 designers, to which 4 responded. In two cases the interview was extended to other members of the project, which was the case of Mush, where one of the partners was interviewed and later on the designer from Furf, the company that developed the design in partnership with Mush, was interviewed as well. In the Fullgrown case, both partners Alice Munro and Gavin Munro were interviewed together. The pilot interview happened in May 2021, while the five other interviews happened in June 2022.

Table 6 presents the sample overview: the interviewees and their projects; the organism they collaborate with; the country where they are currently working on; the number of years of experience working with design; the number of years working with design in collaboration with other organisms; and their background.

Table 6 – Sample overview

Code	**Organism**	**Country**	**Years of experience with design**	**Years of experience with living organisms**	**Background**
PILOT Gislaine Maria Lau (Intervém) Felipe de Carvalho Ishiy (Intervém)	Bacteria	Brazil	Graduated in 2021	Since 2019 (4 years)	Bachelor in Product Design
Eduardo Bittencourt Sidney (Mush)	Fungi	Brazil	Since 2008 (15 years)	Since 2013 (10 years)	Bachelor in Engineering of Bioprocess and Biotechnology; Master's in Engineering of Bioprocesses and Biotechnology and Biotechnological processes; Ph.D. in Engineering in Bioprocesses and Engineering in processes
Rodrigo Puppi Brenner (Furf)	Fungi	Brazil	Since 2011 (12 years)	Since 2020 (3 years)	Bachelor in Industrial Design
Gavin Munro (Fullgrown) Alice Munro (Fullgrown)	Plants - trees	England	Since 1993 (30 years) Since 2013 (20 years)	Since 2006 (17 years) Since 2006 (17 years)	Bachelor honours in Furniture Design & Manufacturing; BTEC National diploma in Art&Design; Bachelor honours in English and German
Zena Holloway (Rootfool)	Plants - grass	England	Since 2016 (7 years)	Since 2016 (7 years)	Qualified as a PADI Diving Instructor; Qualified as a Part Commercial Diver. Zena works with underwater photography
Breno Tenório Ramalho de Abreu (Biostudio)	Bacteria	Brazil	Since 2011 (12 years)	Since 2013 (10 years)	Bachelor in Product Design, Bachelor in Biological Sciences; Master's in Art; Ph.D. in Art

Source: Elaborated by the author (2023)

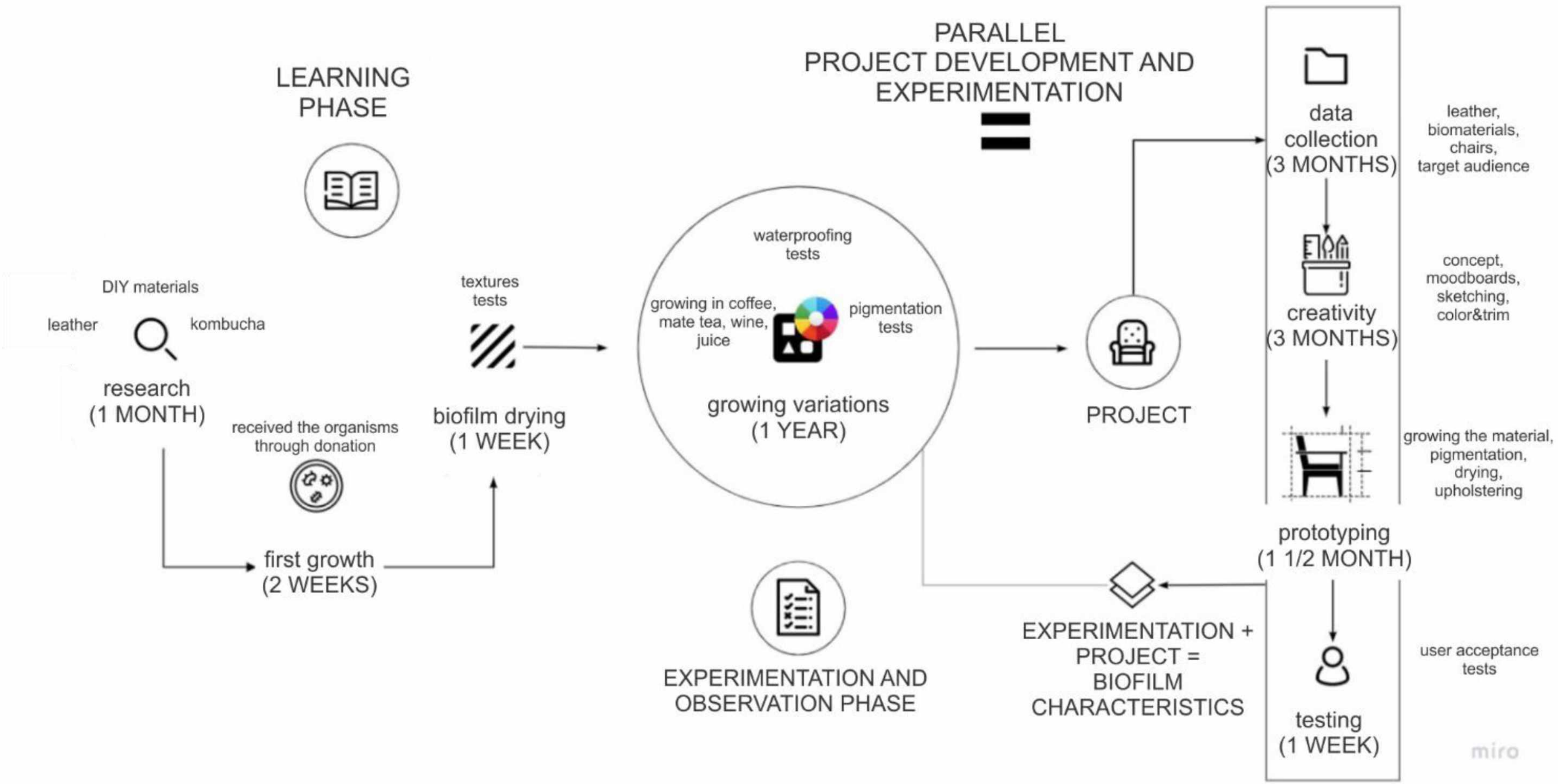
4.3.1 Pilot

For the pilot, two designers from a recently created design studio were interviewed together: Gislaine Maria Lau and Felipe de Carvalho Ishiy. Both graduated in 2021 in product design. Their studio is based in the Southern Brazilian city of Curitiba-PR and develops products from bacterial cellulose and mycelium composite – besides traditional materials.

Sending the questionnaire beforehand seems to have made the interviewees more comfortable and reduced the interviewing time The questionnaire seemed complete in covering the design process in-depth, but some questions triggered answers to others earlier than they were planned in the original script. A follow-up question was added at the end of the interview: “What changes in the creative process when working with living materials?”. Moreover, it seemed important to ask about specific details of the representation strategies for expressing the concepts and detailing the design. Semi-structured interviews offer flexibility to add questions and reorder the script to allow a more comfortable experience for the interviewee. Some questions resulted in redundant answers, but they were kept in the final script because of the different possible project settings in which they could be relevant.

The invitation was made by email and an introduction to the research and its purpose was given. The questionnaire was sent beforehand and a date for the interview was fixed. The designers chose one project to talk about, to which they were requested to provide a graphic representation of the design process (Figure 18). Sketches, renderings, and materials that could be shared were also requested. The interview took about 1 hour. The protocol is described in chapter 3 and the structure is presented in Appendix 2 – Interview Script. As the changes in the script after the pilot study were minor (namely the addition of one question and the clustering of some others), the instrument shown in Appendix 2 is already the reviewed one.

Figure 18 – Design process representation provided by pilot interviewees



Source: Illustrated by the interviewees, our translation (2021)

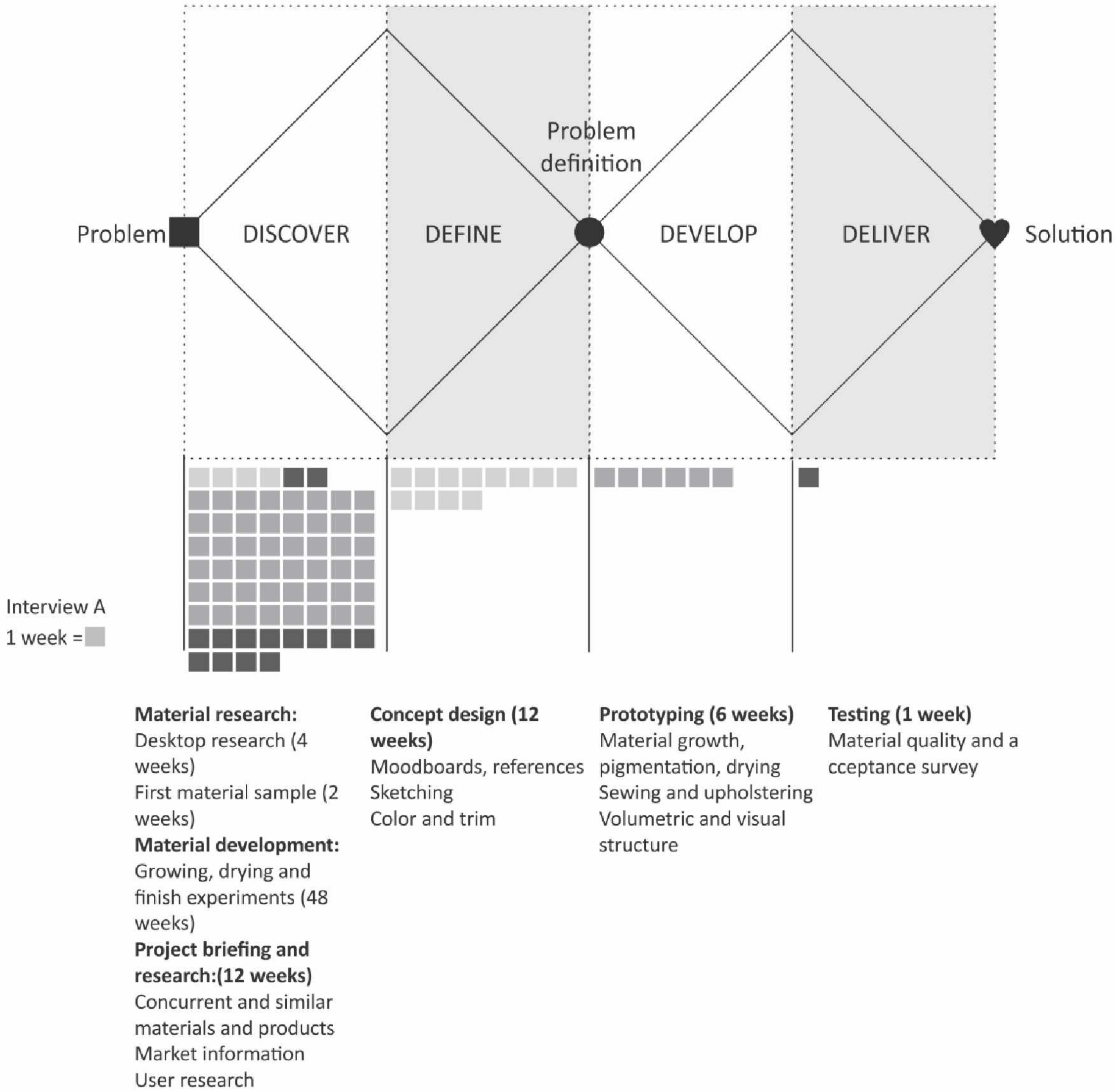
The chosen project was developed in 1,5 years from 2019 to 2020. It received an IF Design Award in 2021 but was not fully prototyped because of the pandemic. It is a chair design briefed on Design Activism principles, upholstered with bacterial cellulose produced by the studio. The starting point of the project was the making of a statement regarding animal abuse, so they began looking for an alternative to leather. The prototype was made of the final bacterial cellulose material, but the metal parts were not produced, only mockuped (Figure 19). It was possible to notice that growth and experimentation with the material, the material development, was the lengthier part of the project and took place at its beginning. In the interview, designers emphasized production bottlenecks and representation strategies, such as the use of digitally-produced renderings with photographed textures of the real material, to assist decision-making in form-giving. They reported that if they could change anything in the project, the user acceptance survey would have been done at its beginning. To develop the material, Gislaine and Felipe explained that they relied much more on their own experiments and desktop research than on the consultation of specialists.

Figure 19 – Não Fere chair design mockup

Source: Image courtesy by Gislaine Maria Lau and Felipe de Carvalho Ishiy (2021)

After the interview, a representation of the interviewees' design process in the Double Diamond Framework through the Mosaic Method was sketched (Figure 20). It is important to notice that this was a previous version of the analysis framework, where the PDP model was not considered yet. During the data treatment process, it seemed difficult to obtain a clear, detailed description of all tasks, their inputs, and outputs as originally proposed by the Mosaic Method. It seemed that such an effort would probably fatigue the interviewees. This is why the original discrimination of tasks, events, process chunks, and stages was not kept for the analysis framework – instead, all items listed and accounted for by the interviewees were considered as process elements. It was up to the researcher to distribute these elements throughout the design process analysis frameworkAlthough not as precise to the original idea of the Mosaic Method, it was understood that this process representation respects the designer's organization of the project in a timeline as much as possible, showing a proportional duration of each phase.

Figure 20 – Pilot representation of the design process in the Double Diamond Framework



Source: Illustrated by the author (2021)

For the representation of the design process models, it was decided that a linear disposition of the time units side by side would give a better idea of the weight in time in each phase. Also, the representation of the project phases in the design process models should didactically follow the Double Diamond but also the PDP phases.

The completion of the pilot showed that the method could satisfactorily fulfill this study's aim and objectives.

4.3.2 Design process in collaboration with mushrooms

The first interviewees were Eduardo Bittencourt Sidney from the company based in Brazil, Mush[13], which develops mycelium composite products; and Rodrigo Puppi Brenner, from Furf[14] Design Studio, also based in Brazil. In partnership, they developed the acoustic panels Iris collection, in 2020. Eduardo's background is in Engineering of Bioprocesses and Biotechnology and Rodrigo's is in Industrial Design. Eduardo has 10 years of experience collaborating in designs with other living organisms, while Rodrigo is working with them for 3 years. Besides Eduardo and Rodrigo, Mush and Furf's teams participated in all project phases. Eduardo and Rodrigo were interviewed separately in June, each interview took about one hour. For didactical purposes, the information from both interviews is presented together in this section and Table 7 offers the project summary.

Rodrigo provided a sketch with the design phases and their duration, which were compiled with the information given in the interview into a design process model presented in Figure 21. It is possible to notice that the longest phases of the process were Define and Develop. In this project, Define corresponded to the Conceptual phase of the PDP model, while Develop corresponded to the combined phases of the Detailed Project and Preparation for Production. The phases are further described in the next paragraphs.

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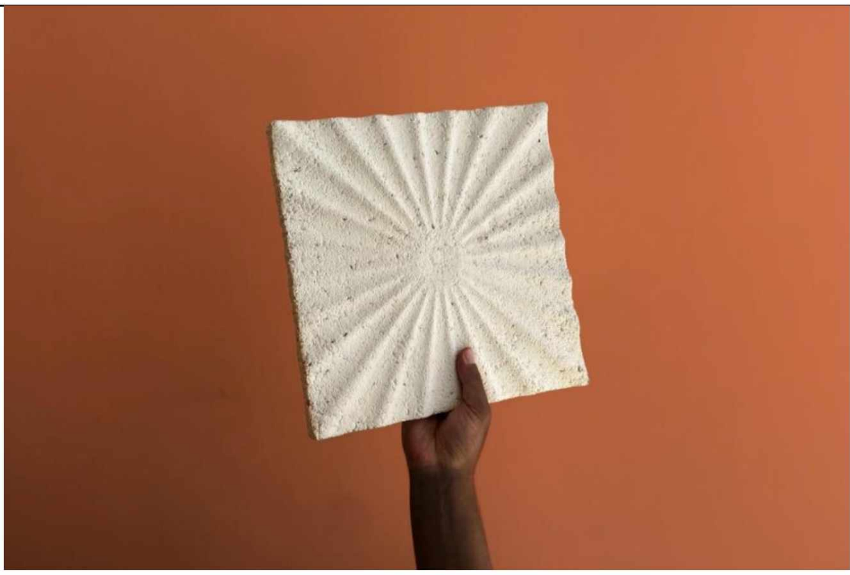
[13] MUSH. Website. Available at:< https://mush.eco/>. Accessed on January 16, 2023.
[14] FURF. Website. Available at:< https://furf.it/>. Accessed on January 16, 2023.

Table 7 – Furf and Mush project summary

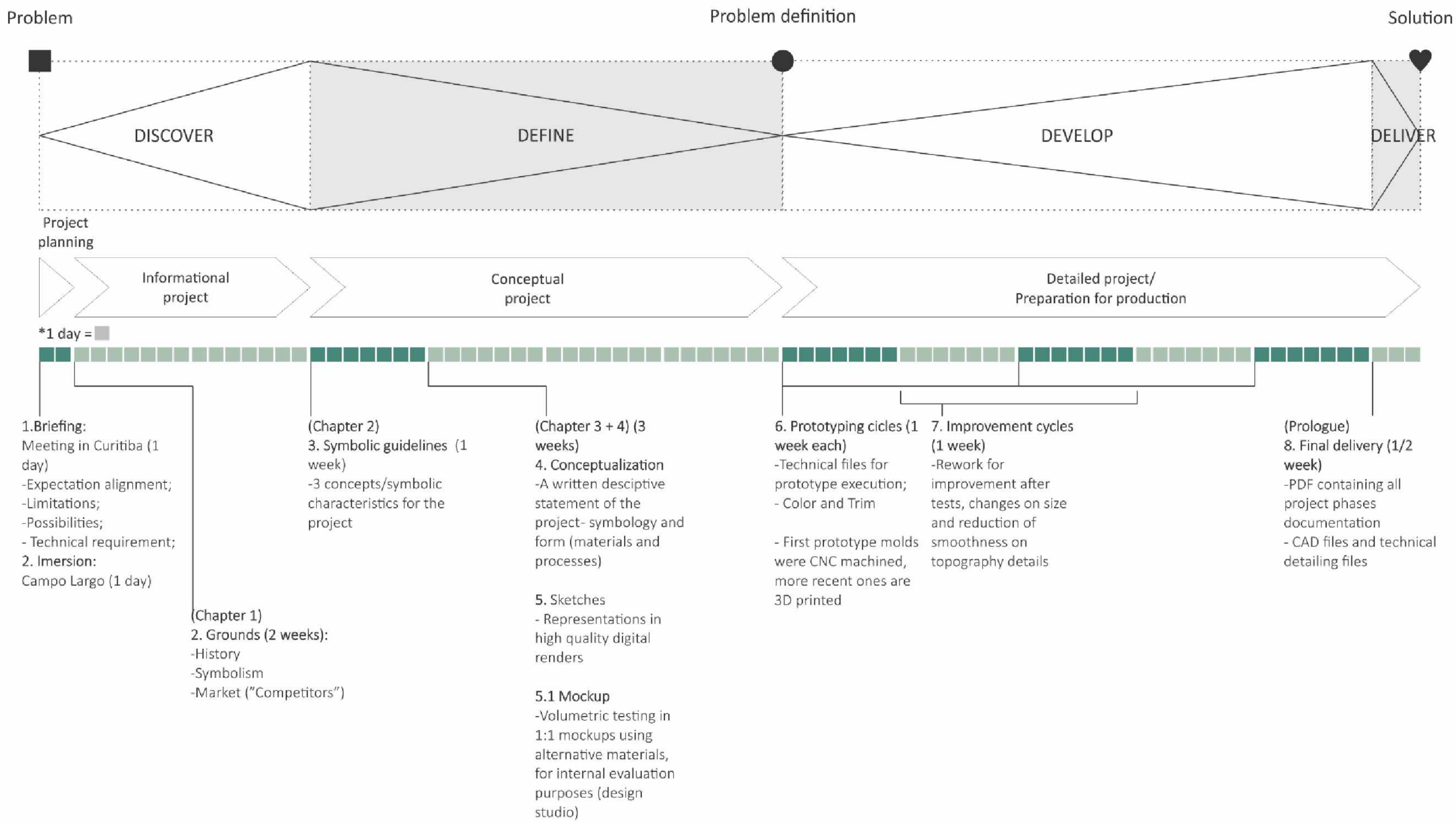


Source: Courtesy of Rodrigo Brener (2022)

PROJECT NAME: Iris Collection	
YEAR: 2020	DEVELOPMENT DURATION: 7 to 8 months considering the technology, 3 months for the Iris collection design itself
BRIEFING OVERVIEW: Mush is a startup that emerged and grew in the Federal Technological University of Paraná's context, it was originally thought to address the packaging industry. For this project, they wanted to develop their first product as a company - and at the same time develop their technology to a market-ready level. Mush already had characterized their material, they knew the material's properties, and they wanted a product that was sustainable, beautiful, and that had some kind of function for the final user. One of the properties found in their material was noise absorption, which was the characteristic they emphasized in the briefing. Eduardo and his team had noticed a lack of sustainable and beautiful products in the acoustic market – thus they defined the product's application: acoustic panels. Hence the briefing for Furf Design was to develop a product with added value, which could be commercial and sellable. As acoustic panels are used in offices but also in home offices and homes, Furf proposed to Mush at the very beginning that they directed the collection to Architects. Mush was the first company to enter the mycelium market in Brazil.	
MATERIALS AND PROCESSES: The first molds were CNC machined in ABS. In the sequence, molds were 3D printed in PLA and ABS. Finally, molds were vacuum formed in PETG. Different residues were tested as substrate and ultimately sawdust was used. Different fungi species were also tested.	
PRODUCT DIMENSIONS: 30x30 cm	BATCH SIZE: Approximately 600 units by the time of the interview

Source: Elaborated by the author based on the interview (2022)

Figure 21 – Mush and Furf Iris collection design process



Source: Elaborated by the author (2022)

Discover

After Mush and Furf's first meeting in Curitiba, they kick-started the project with a field trip at Mush in the city of Ponta Grossa. Furf got to know the company, the lab they worked in, and they collected mushrooms in the forest together, in an immersive experience.

The development of the material began in early 2019 – completely done by Mush. Mush had already its laboratory routine and processes established when the project began: they had tested different fungi and different substrates, which always originated from some industrial waste. In 2020, for the Iris project, Furf followed up and made suggestions on what substrate could give the look which could be more interesting for each public.

Rodrigo tells that in the beginning, Mush had already presented to them existing possibilities and characteristics of the material and its main applications. Eduardo remarks that Mush had previously studied the market for acoustic panels: the price of existing products, their specification, the target audience, and market influencers. The company Mogu was their benchmark. Furf looked into available information on the internet and began the process of developing a strategy to differentiate the product and the brand. They strategically researched what were the late developments in mycelium, and people's perception of it. Symbolical and aesthetical characteristics that the product could express in its strategy were looked into, like a futuristic expression. Furf also inquired among architects, and their target audience for the Iris project. Rodrigo reveals that they have a very particular design methodology at Furf: "[...] *we call the introduction a preface, each of the phases are chapters. So it has to be a super-linear narrative that we are going to tell* [...]" (Rodrigo). In their process, research categories are not separated - but trends, consumer information, and so on, are all intertwined in the narrative of the project.

For the research of the concept, Furf developed a presentation with many art, gastronomy, and even architecture references – but few direct design references. There was a meeting with Mush where the research base for the project was presented, "fundamentação", which will be here translated to "project foundations", approved on this occasion.

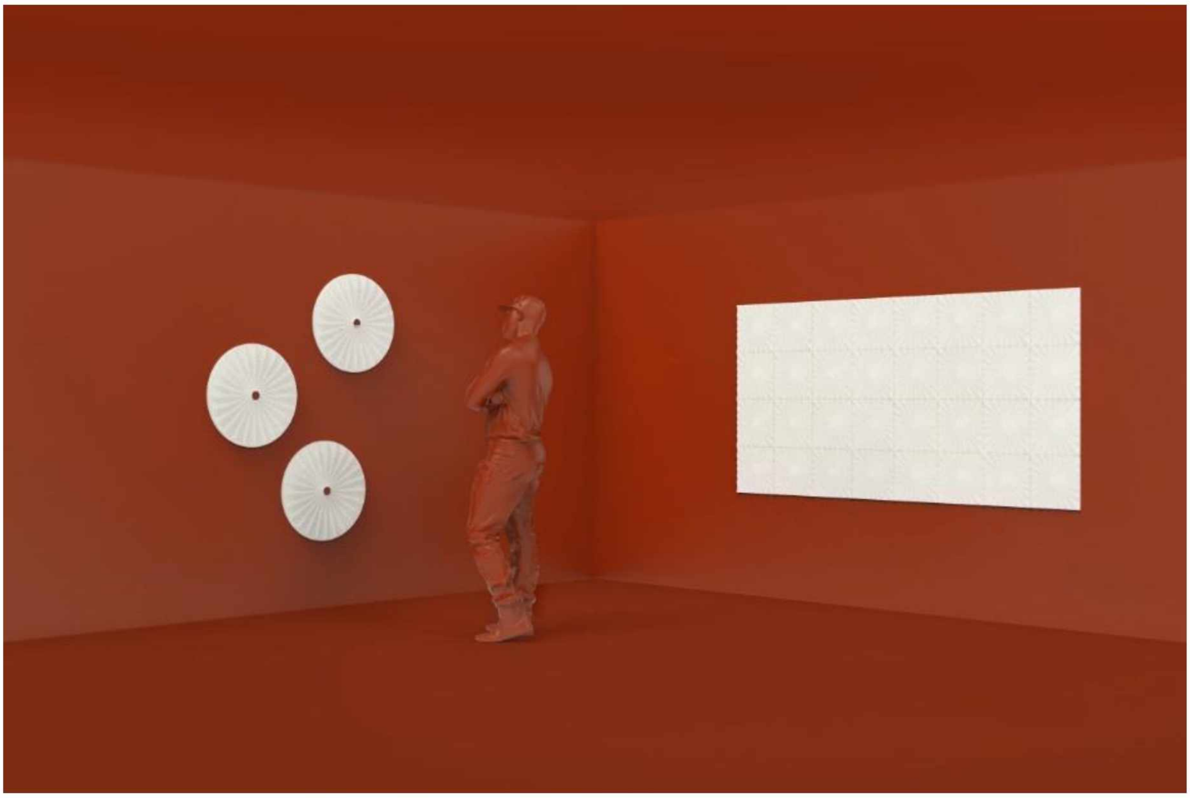
Define

After the approval of the project foundations, Furf's team worked on the definition of the symbology and concept for the project. Succeeding a new meeting with Mush, where the guidelines for the design were approved, they began to sketch.

The concept had a futuristic appeal: "[...] *in a very pragmatic way, but really the future itself asks to be sustainable for us to even have a future. We need to be sustainable. So, for us, sustainability asks to be futuristic. We will always use sustainability in materials, not with a zen appeal, like a hippie thing.* [...] *Sustainability does not sell itself.* [...] *But then, any human being is more willing to pay much more for a product, which is much cooler, which is very dıfferent, which has a breath of fresh air, a futuristic one. In Mush, this is a very strong feature. We do not use sustainability as an anchor,* [...] *that it is sustainable is the cherry on top. The architect will want to use the mycelium because it is a technological material, made in a laboratory, made by a startup*"(Rodrigo).

Sketching was relatively brief for this project. It was done in one day, using a team of three people. They sketched the proposals for the designs and selected one option, which was then presented in digital renderings for Mush. The concept was inspired by the field trip they had made at the beginning of the project: "*We were in the middle of the forest and a sunbeam came in, and it made that lens flare, that circle,* [...] *And that stayed with us,* [...] *and we were always talking about a new vision, a new project vision. And being very literal, well, vision is associated with the eye* [...]. *And one of the most beautıful parts of the mycelium, of the mushroom, is actually when you take the hat off and you see the lamellae,* [...] *It's a circle. It's crazy how this element repeats in nature*" (Rodrigo). These associations inspired the final design. One of the renders presented to Mush is shown in Table 7 and another in Figure 22.

Figure 22 – Rendering for the iris collection



Source: Courtesy of Rodrigo Brener (2022)

The 3D modeling for the presentation of the concepts was done in Rhinoceros, and the final design for mold production was 3D modeled in SolidWorks.

The approval of the proposal for the design collection was unanimous among the Mush and Furf teams.

Develop

After defining the substrate, the fungi, and the process, the next challenge was to develop the molds: "*the types of molds we could use, what worked and what didn't,* [...] *the level of detail of the products* [...] *was something that took a little time to get right*" (Eduardo). Many tests were made.

There were not many changes in the design from concept to production. Little changes were made to the product's dimensions, as well as changes in the molds, to achieve the level of detail envisioned for the collection: "*As the mycelium reacts differently depending on what it is mixed with and depending on the material in which the mold is being made, there is no way we can predict, unlike injected plastic, or injected polymer, exactly how the part will* *be* [...] *The mold needs to be a little more exaggerated than the final product in order to achieve the level of detail that we want.*" (Rodrigo). Eduardo observes that some adjustments had to be made in the substrate, in the molds, and growing process so they could achieve the desired results. For instance, they changed the mold's material due to fragility.

Prototyping happened first internally with alternative materials at the design studio to check for volumes and dimensions. After the design team agreed on a design, they adjusted the 3D CAD model and Mush 3D printed the molds and grew the prototype in the final material. In the prototyping phase, both teams worked closely: Mush had continuously sent samples to Furf showing the improvements and tests with the material. Eduardo and Rodrigo tell that they had about four cycles of improvements with the prototypes. One strategy was to do the prototypes in a smaller size, rather than the product in its final size.

Eduardo explains that they knew the product was ready when they achieved in their tests the visual appeal and aesthetics they had intended for the collection.

Deliver

When the product was almost ready to sell, a market validation was made: they research the market's needs for acoustics. Today Eduardo concludes that Mush is going through a marketing fit phase: to effectively sell and to understand how the product relates to the people.

Other product validations were outsourced: compostability, biodegradability, carbon neutrality, compression, flexure, combustion, and acoustic absorption. For those tests, Mush developed specific samples. These validations helped to develop other technologies inside Mush. In the end, Mush got a product that has the function of acoustic absorption, but that also insulates the environment thermally and is resistant to flames. When the product was already fully developed, they got access to a sample of Mogu's product for comparison.

The final molds for production are vacuum formed and are also outsourced.

When asked about what he would have done differently, Eduardo explains that acoustic boards usually have a size of about 1 meter to 65 centimeters, while Mush's board has about 47 centimeters. He explains that this was a technical limitation at the time, but today he would like to have made it differently – according to the already established standards.

Challenges and bottlenecks in the project were the lack of a reference model in Brazil, and the lack of space and resources. The project began in a university laboratory, where many learning, extension and research activities happened in parallel. One of the most difficult parts to get right, according to Eduardo, were the molds: to achieve the desired definition in the designs, features, and geometries had to be exaggerated.

In retrospect, Eduardo evaluates that the main design decisions in this project were the definition of the type of product to be made and the quality level to be achieved in the final product.

Teamwork happened throughout the project. Mush's team consisted of 3 partners at the beginning, and after getting funding, it grew to add more 11 collaborators. Meetings between Mush and Furf at the beginning of the project happened at a frequency of every 15 days, later they came to daily exchanges due to laboratory results, to finally become monthly meetings.

Eduardo observes that he developed an instinctive feeling to look at a design and evaluate if the details will appear on the final grown piece or not. From the beginning of the Iris project to now, they changed the way they conduct prototyping in their design process. Today, Eduardo explains, they 3D print the molds in miniatures with different levels of detail.

To young designers who wish to collaborate on projects with other living organisms, Rodrigo advises not to imitate famous Brazilian designers, but "to find another angle*, to look where nobody is looking,* [...]*. And when we really want to innovate, we need to look at the science*". Rodrigo advocates that design has the spotlight that science needs, and with science comes true innovation in design. Science and design make a great "couple", Rodrigo says. He completes: design can help people understand and "want" the science: "*the main advice related to biomaterials is to talk as much as possible with scientists*". Eduardo also advocates for the intersection of design and science: "*If I were to give a recommendation to designers, it would be to try to participate actively in unconventional technologies*". Eduardo encourages young designers to live and experience different and new technologies, and to get to know them in-depth.

4.3.3 Design process in collaboration with plants: trees

The next interviewees were Alice Munro and Gavin Munro from Fullgrown. Fullgrown is a project based in England, which designs and develops objects in collaboration with trees. A key characteristic of Fullgrown's design process is that it is very experimental. As Gavin explains: "*is gonna work by being there, doing it*". Gavin's background is in Furniture Design, while Alice's is in English and German. Gavin and Alice have been designing with trees for 17 years now. He is the one who had the initiative for the project and does the design concepts.

The interview happened in June and lasted almost two hours, Alice and Gavin participated together. Table 8 offers the project summary for the chair designs. Gavin sketched the design process, which again was combined with the interview information into a design process model in Figure 23 and Figure 24.

Table 8 – Fullgrown project summary

Source: Fullgrown (2021)

PROJECT NAME: Fullgrown. Each piece is named after a person. The first prototype was named after Alice's mother, Vaila.	
YEAR: 2006	DEVELOPMENT DURATION: 11 years
BRIEFING OVERVIEW : [About the beginning of Full Grown] Gavin Munro's work is autobiographic. When he was little he had a spine problem and had to spend a long time at the hospital. Out of the hospital's window, Gavin tells he could see	

Table 8 – Fullgrown project summary

trees, birds, and other wildlife that was as well cared for as the patients in the hospital. Also, he remembers seeing an overgrown bonsai shaped like a throne in his grandmother's house. These are the moments that he remembers as the moments where his history with trees began. After Gavin's graduation, he started building furniture out of driftwood. Eventually, he spoke to Chris Cattle, which was designing and shaping trees as they grew into furniture. After a journey of reflection, Gavin decided he would try it himself: instead of cutting trees into pieces and building furniture from them, he would grow the furniture. A friend of his pointed out, like Gavin also had to wear a metal structure, "a mold", to help him with his spine problem - he now shapes the trees into furniture with molds as well. The briefing was to "*pick up where Shaker design and William Morris design left off. The idea, in the beginning, was just to be able to make solid, usable chairs.* [...] *but we really* [were] *just trying to make ordinary chairs like you are sitting in now. Because* [...] [if] *we grown them into one solid piece, they are grafted together, these are chairs that could last* [...] *hundreds or thousands of years* [...]" (Gavin). The price estimated for the chairs was hoped to be a few hundred dollars for a piece that would last for generations, being the public "affordable middle class", "*basically an extension of Shakers and the Arts and Crafts movement of a "normal" object in a home*" (Gavin). However, after realizing the difficulties of growing a chair and all the poetics and ecology it involves, Alice and Gavin rethought their grown objects within artistic terms. The estimated production price of a piece is currently several hundred thousand dollars.
MATERIALS AND PROCESSES: CNC-machined Correx molds were used to shape the trees. Correx is a two-walled fluted polypropylene sheet. The sheets were folded into place in wires installed at the plantation. To achieve the necessary number of branches the coppicing technique was used. In this technique, one begins allowing the tree to grow, aiming for a healthy root system. After this growth period, the trees are cut low down in the winter. The tree shoots new branches in the spring, trying to match the root system. To naturally "weld" the branches together, grafting techniques were used. In these techniques, parts of two or more branches are carefully cut, then secured into place to heal together. They shaped the tree branches along the molds with fencing metal staples, which were hand covered in foam. After some years, the staples were removed to allow the branches to thicken. The tree was then harvested, let to dry out, sanded, and polished.

PRODUCT DIMENSIONS:	BATCH SIZE:
Approximately 70x70x100 cm	Ideally, Alice and Gavin had 350 chairs growing, but due to a design problem and growing issues, their next batch will have approximately 7 chairs.

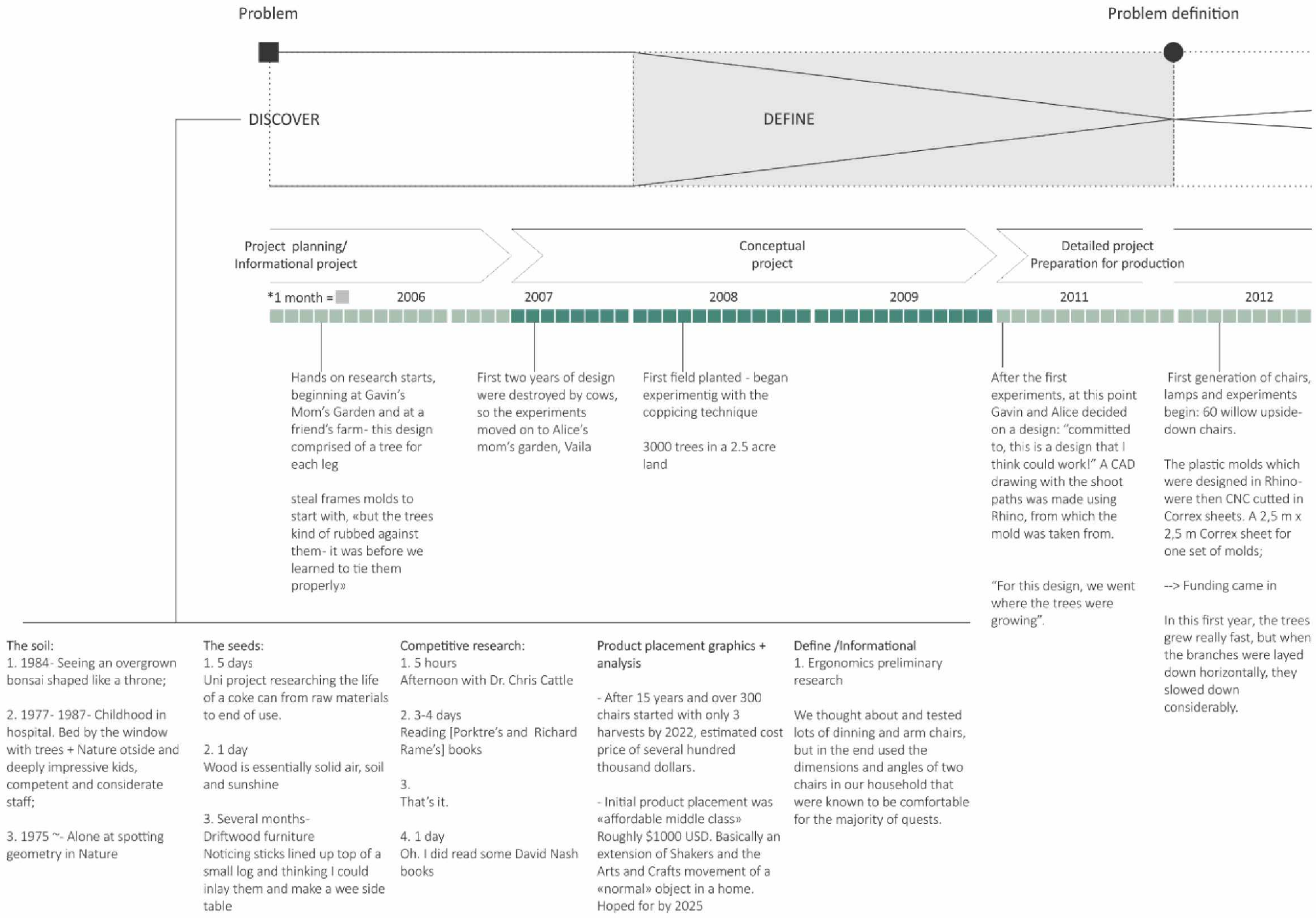
Source: Elaborated by the author based on the interview (2022)

Figure 23 and Figure 24 show the design process timeline. Each month is represented with a little square, so it is possible to visually understand the weight in time that each design phase has on the entire process.

The Define phase began when Alice and Gavin decided on turning the chair design upside down and it continued until the moment they opted for one design and began to work in the field to grow the first batch of trees for this design. The Develop phase seemed to be by far the largest of the project and did not seem to correspond to a specific PDP process phase. This phase looked more like a production follow-up, where design decisions were made in collaboration with the trees. The Deliver phase began when the prototypes were harvested:

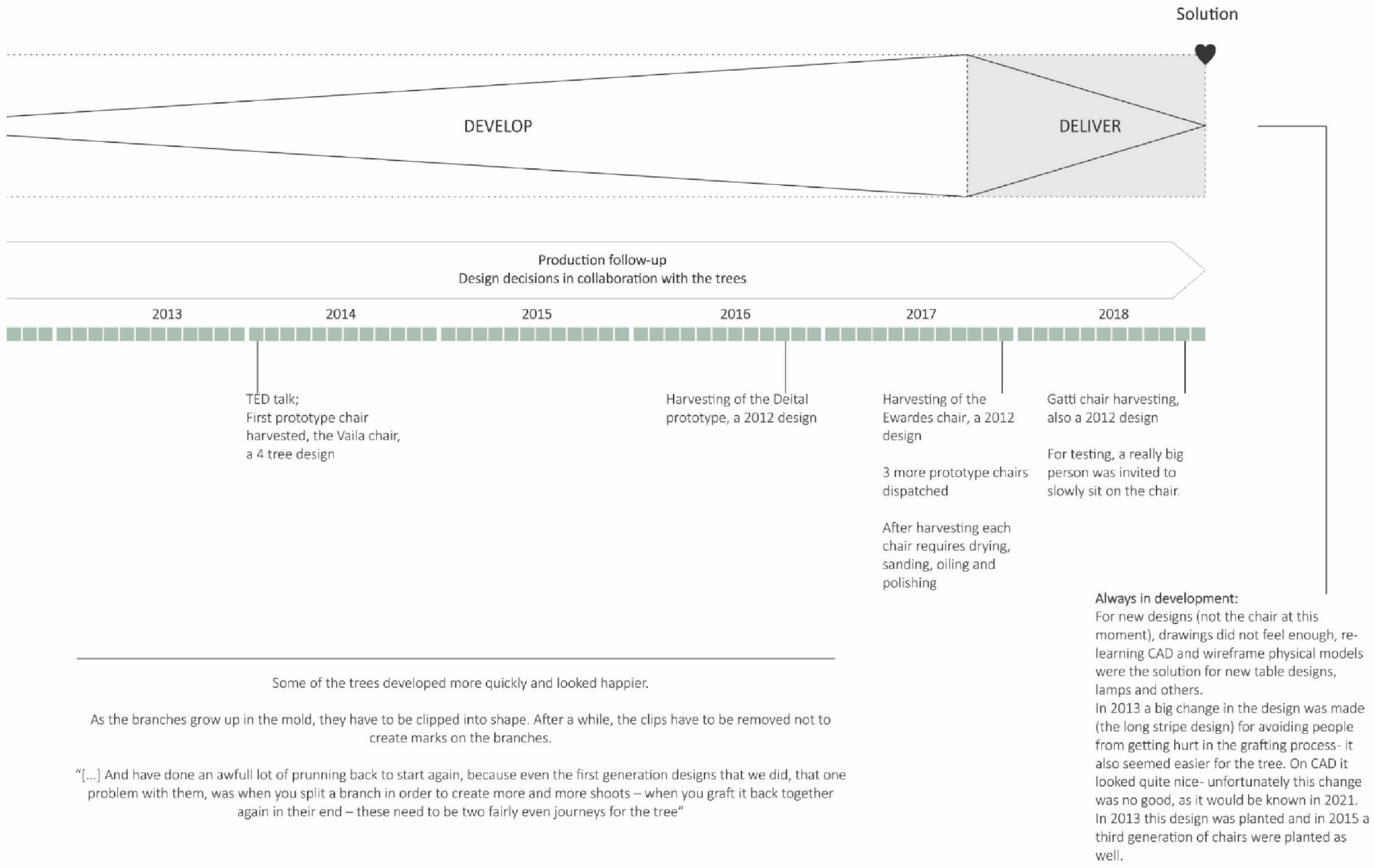
the Deital, the Edwardes, and the Gatti chairs. The process is detailed in the next sections and some quotes from Gavin and Alice Munro’s interview are included.

Figure 23 – Fullgrown's first-generation chair design process (part I)



Source: Elaborated by the author (2022)

Figure 24 – Fullgrown's first-generation chair design process (part II)



Source: Elaborated by the author (2022)

Discover and Define

Experiments in tree shaping began in 2006 when Fullgrown got a small investment from a friend. The first tests were done in plant containers in Gavin's mom's garden and on a plot of land on a friend's farm. Sadly, those experiments got ruined by cows and rabbits after 2 years. Thereafter, they began again at Alice's mom's garden, where they started having good results.

The first design consisted of one tree planted for each of the four legs of the chairs. They used steel frames as molds, tying the branches along them (Figure 25). This design was not ideal because it resulted in competition for light among the trees, which were planted relatively close to each other. This is why they changed the design so they could grow only one tree for each chair, turning the chair upside down (Figure 27). To achieve the necessary number of branches, the coppicing technique was used. According to Gavin, one knows when the tree is healthy when the coppicing works. Gavin and Alice began the coppicing process in 2008 with 60 trees, in 2012 they started to shape them with Correx molds. The molds were CNC machined and plied into shape with wires (Figure 26). This "upside down" design seemed more "comfortable" and successful for the trees. At this point, in 2011, Alice and Gavin decided on a design in which they would shape the chairs. Figure 28 shows how the branches were clipped onto the Correx mold.

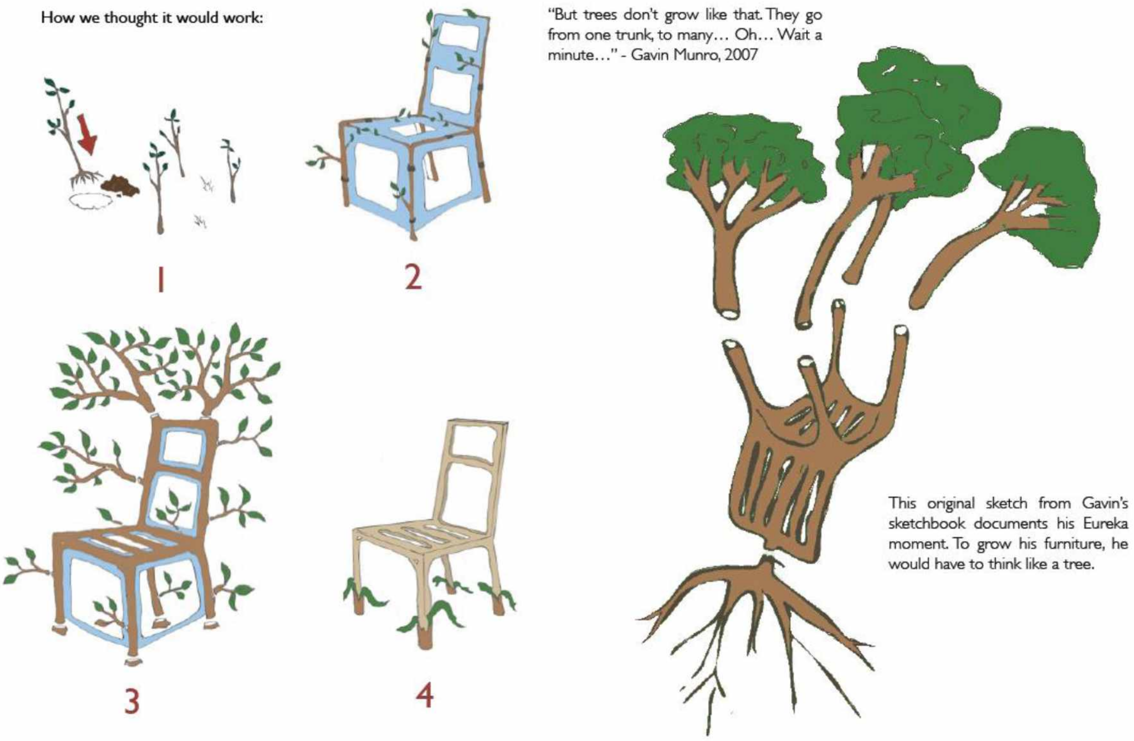
Figure 25 – Steel frames as molds.

Source: Fullgrown (2017, p.17)

Figure 26 – Correx molds.

Source: Fullgrown (2017, p.20)

Figure 27 – The change from one tree for each leg for one tree for each chair.



Source: Fullgrown (2017, p.16)

Figure 28 – Branches clipped on the Correx mold.

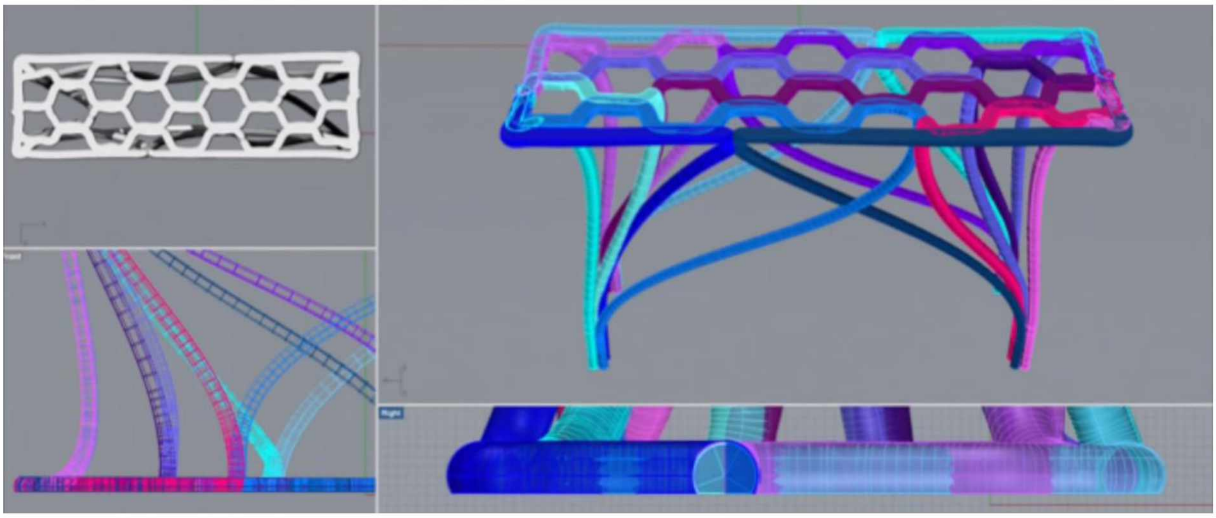
Source: Fullgrown (2017, p.32)

Regarding the concept and product expression references for the project, the first inspiration came from a chair that a friend of Alice's father had made for them when they got engaged. This chair had a Windsor chair look. Gavin mentioned that the initial brief was "*wanting to kind of pick up where Shaker design and William Morris design left off*". Another reference for them was a chair they had in the office that was comfortable. With regards to the finishing: "*this is where we pick up from where the shakers left off, and I love midcentury design, I am very keen for the outer surfaces to be very clean and crisp and geometric. So it complements the organic nature of the construction* [...]" (Gavin).

Considering trend references and studies, Gavin and Alice tell that they did not really take this kind of data into consideration at the time, because Gavin was more concerned to develop this new and different technique of making. Alice says that now, in the background, they look a little bit "*at luxury markets and see what other people are creating and [...] what other designers are looking at*" – but this is not a major highlight in their design process.

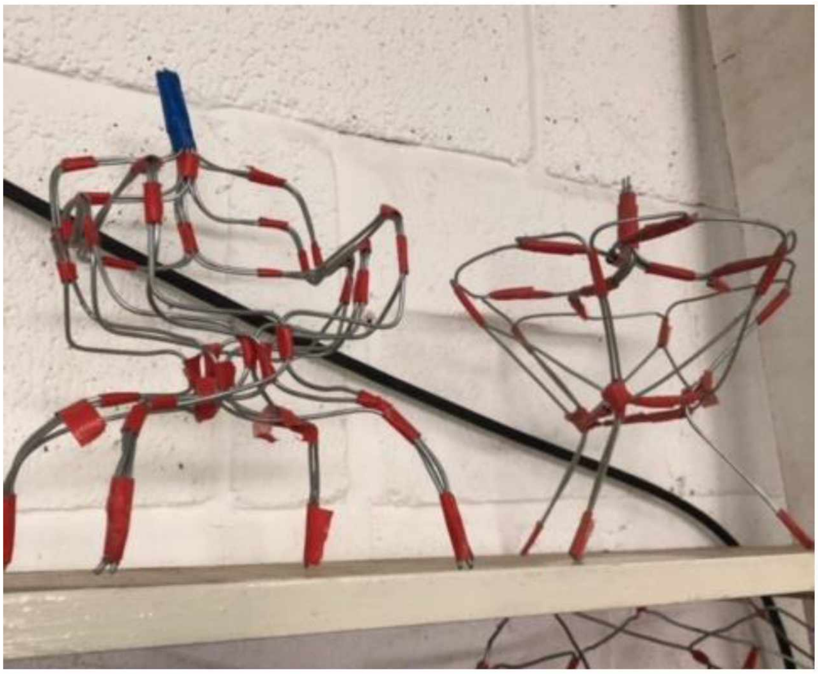
The first ideas were drawn extensively by Gavin. He tells that he soon realized "*that it is really hard to do, essentially a 4D object on a 2D piece of paper, because* [...] *you can draw a 3D object on 2D paper but trying to draw how it will grow, that was an extra level. That's when CAD Rhino came in and then just designing the shoot paths* [...]". An example of one of Gavin's CAD models is shown in Figure 29. Later on, the CAD modeling process presented some difficulties too and Gavin began using wire-shaping techniques to develop his new designs (Figure 30). The software Gavin used in the development was Rhinoceros, he used it to simulate the shoot paths of the branches. After that, he designed the Correx molds in Rhinoceros accordingly. The CAD models were used to CNC the Correx molds.

Figure 29 – CAD model by Gavin Munro.



Source: Munro (2014)

Figure 30 – Wire models by Gavin Munro.



Source: Image courtesy from Alice and Gavin Munro (2022)

The design process followed on the field: the branches were arranged and grafted as the trees grew. Each new branch that grew was a design decision. "[...] *So as the trees grew, we started following the pattern, but the trees have their own idea of what they want to do*" (Gavin). Currently, there are two designs growing simultaneously: one that began to be shaped in 2012, and a new design, which shaping began in 2013. The 2012 design is symmetrical and branches were arranged and grafted intuitively, whilst, for the 2013 design, there was a pre-defined pattern to be followed.

Develop

The 2013 design was a big change in relation to what Fullgrown was already doing: it was called “the long stripe design” (Figure 31). This design seemed to be “easier” for the trees and easier for the process of shaping and grafting: with fewer design decisions to be made at each new growth. As Gavin described it, it had a “euclidian” and an “ideal” design feeling in it. However, in 2021, it was realized that with the long stripe design, the tree grew out of shape in the penultimate year before harvesting. The seat grew on an uncomfortable convex shape and there was too much overgrowth behind the knees. Hence, in the near future, all the trees shaped in the 2013 design will have to be cut back and regrown.

Figure 31 – The 2013 design, the “long stripe design”.

Source: Image courtesy from Alice and Gavin Munro (2022)

At the same time that the 2012 design was turning out successful, there were still some challenges to deal with grafting during the development of the trees: "*where one of the branches* [...] *went straight up to the chair's back and the chair's leg and one of the other branches went along the chair's seat and then back again* – [...] *so one is longer, so when you graft them back again together, the tree doesn't want to grow along with the longer shoot. It stops growing*" (Gavin). In those cases they had to start again, cutting the tree back down to the chair seat level and hoping the tree agrees to the change. What brought difficulty to the process is that it can take up to 8 years to see if the man-made changes to the tree "worked". At the first glance, the tree seemed to have responded well, but in year 6 the tree began to bend in the wrong direction: "[...] *Trees just don't stop. We think they don't move very much but they are all over the place*" (Gavin). The way they dealt with this is: "[...] *there is now a point where we* [...] *have to keep the branches apart before we graft them together, but nearby each other, so you can bring them back together to graft. Actually, that's a technique that we have not yet mastered. That's next stage, we dropped the proof of concept, but the proof of scaling, this is a solution that we need to figure out*".

Another difficulty Fullgrown had to tackle is the difference in growth among the trees. Some of the trees grow quicker into chairs than others, and the exact reasons remain unclear. But Gavin tells about a lot of things he has learned in the process: "[...] *now I know about the even things grafting, about the kind of mirror symmetry design, then the morning sun and afternoon sun is evenly distributed".* They also learned about how to level the amount of stress they submit the tree to. Gavin explains: "*So* [...] *the first ways that we were doing it we were a bit too, essentially aggressive for the tree, but that's not that simple, because we're starting to think actually what you are replicating is a storm, which is kind of a very violent thing. So sometimes we are being too gentle with the branches and actually, that's what caused the problem*."

Deliver

Finally, the Gatti chair, a 2012 generation design was harvested in 2018 and is considered by Fullgrown a very satisfying result. This model was submitted to empirical tests with people sitting on it.

Outsourcing activities happened in the project in the Discover and Deliver phases. The CNC machining of the Correx molds was outsourced and Gavin and Alice had the help of friends in preparing the staples they used to fix the branches on the molds with foam.

When asked about what they would have done differently in the process, Gavin replied: "*I would have stuck with my instincts in that first design, kept with that.* [...] *That's what I would have done dıfferently, it was trust myself more. I actually knew what I was doing, I've been thinking about it for years and not to change everything too quickly.* [...]". Eventually, they were so busy with other aspects of their professional lives that they could not be at the plantation, they only received information about what happened there from their team, but they could not be there to observe themselves. Alice emphasized: "*You definitely got to have time to be there because we have been focusing on other things and we regret every time we don't go there*". Gavin continued on the importance of paying attention: "*But is not just the tree. It's the whole ecosystem in which the tree lives in. So when I started it, I was just kind of like "it's just grass on the ground and the trees, and that was that" but actually that made the soil more compact and dryer and it's when Alice started planting other things and having more of the kind of holistic view of,* [...] *you are actually kind of creating the soil, which creates the tree, which creates structures, which we then try to adapt.* [...] *This is where looking and listening to what's going on is really important*".

The main bottleneck in the project is considered the cash flow, because of the long time the development of one single product takes.

About the design decisions in the Fullgrown project, Alice and Gavin tell that some of the design decisions were made at the very beginning, but each tree needs its own design decisions as well. Gavin says: "*Designing the chair up front, with the angles and where the arms are,* [...], *and then you realize the tree wants to do its own thing*". About the design decisions in the second generation design, Gavin explains: "*we had the right angle for the back and even had enough to compensate for a little deep* [part of the seat where you sit in], *but the tree didn't want to grow in that way, well it did to start with* [...] *but over five years after you did that, then it starts to* [...] [the chair seat] *the branch started to push up, then you've got a lot of design decisions of on how to bring the branches back and this is where you start to realize that what we are actually doing is replicating a storm, to some degree* [...]".

Along their way in the project, Alice and Gavin consulted some people: like Ian Sturrock, a grafting expert; Joseph Clements, a student from Kew Gardens who wrote his dissertation on tree-shaping; an expert from Kew Gardens gave some advice before the lecture Gavin spoke there; David Nash – who explained to Gavin that Fullgrown was art and not manufacturing - which was a massive turn in his creative process; and Jo Stanistreet and Ned Wiltshire, which are Alice and Gavin's landlords.

When asked about what changed in their design process after working with living materials, Gavin explained that it was the way that they saw what they do entirely. When they began, Gavin thought he was very focused on the creation of a new manufacturing system. But after talking to David Nash, he learned that what he was doing was an art: "*Was realizing that it's not just design, it is sort of art and ecology, and all of these things have to be considered and taken on board in order to go past that [...] You are actually interacting with the animals that live there [...]So actually, we are not trying to change manufacturing, we are actually trying to change how we talk and act to each other and how we interact with the natural world completely.*"

For students that want to work with design with living organisms, Alice and Gavin advise that the world view that they introduced previously is very important: it is not just design, it is also art and ecology. Additionally, Alice comments on the importance of patience and enjoyment in the process: "*Being able to play and actually feeling affection and loveful,[...] you do need to care about that organism a bit.* [...] *And you have to have time to play, time to enjoy, time to observe*". Gavin also advises writing a diary "*simple things are very important*". Finally, Gavin speaks about a possible design principle: "*In the same way that like a thing is good when you can't take anything else away,* [...] *what is the most subtle interaction we can have with the environment in order to create the things we want*"? He explains that some interventions they did that they thought were subtle, after some years of experience realizing that while they were being subtle with the ecosystem in general they had ended being "*quite brutal*" with the trees themselves, and while understandable at the time Alice and Gavin would not like others to make that particular mistake.

4.3.4 Design process in collaboration with plants: grass

Zena Holloway's and her Rootfull[15] initiative was the following interview. Zena develops fashion pieces and objects grown in grassroots. For this interview, she talked about the development of her dresses and also an earring. The project summary is given in Table 9. Zena has a background in diving and underwater photography, and it's been 7 years since she works in collaboration with other living organisms.

The interview happened in June 2022 and lasted about one hour. Information from her website (HOLLOWAY, 2022) complements the details of the project.

Table 9 – Rootfull project summary

Source: Zena Holloway (2022)

Table continues next page

[15] HOLLOWAY, Z. Rootfull website. Available at: https://zenaholloway.com/root. Accessed on January 18, 2023.

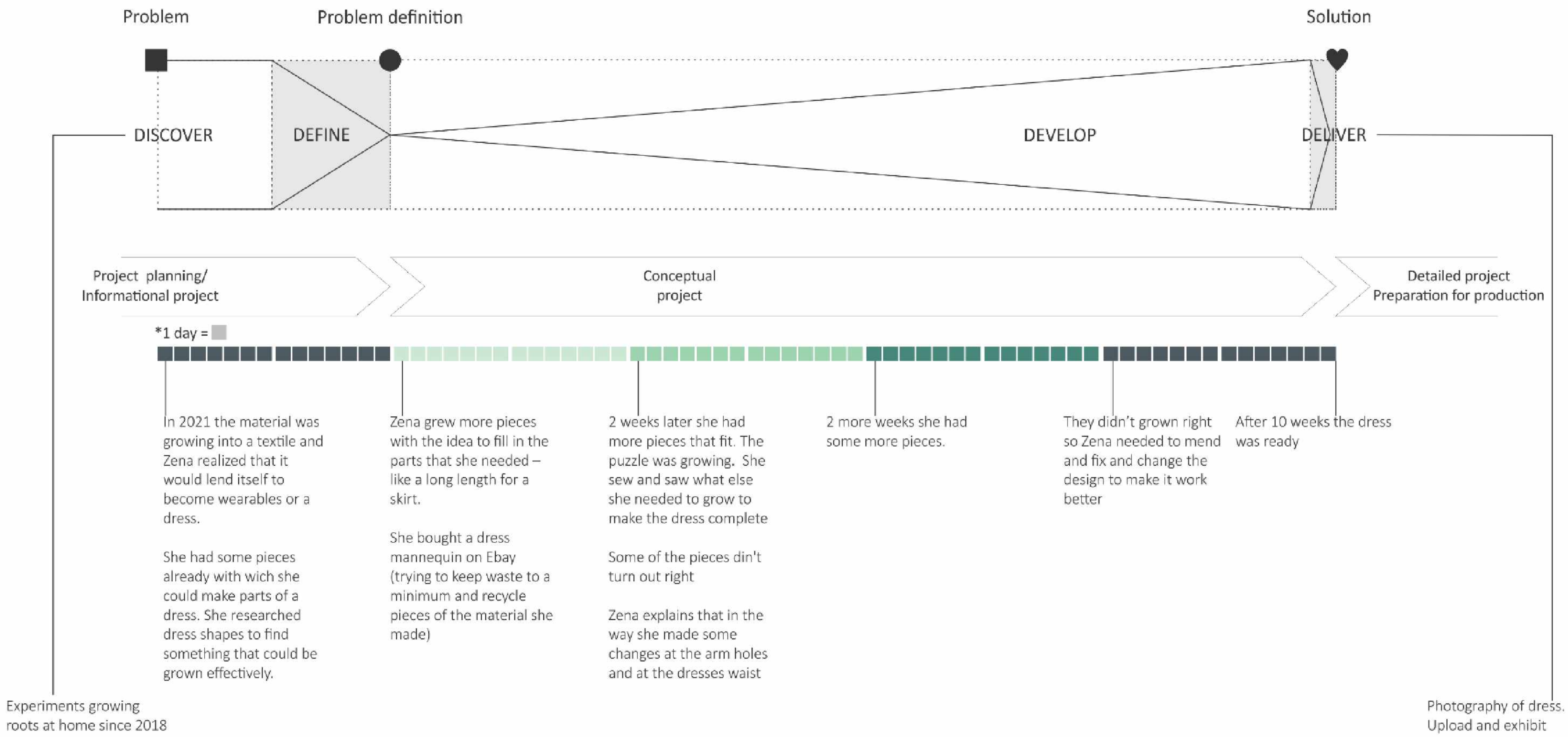
Table 9 – Rootfull project summary

PROJECT NAME: Rootful wearable collection	
YEAR : 2021 (began in 2018)	DEVELOPMENT DURATION: 4 years since the beginning of the experiments, 10 weeks for the dress
BRIEFING OVERVIEW Zena's work is authoral and experimental. The process was not product oriented, the material application came in later. Her website describes: "Rootfull is about growing memorable artifacts across fashion, art, and design that question our material choices and inspire sustainable solutions" (HOLLOWAY, 2022). Zena explained that her interest in biodesign began in 2016. As an underwater photographer, she witnessed the sea condition decline and fish disappearing. She felt her camera was not enough, that it did not raise enough awareness. Zena tells: "*The way to inspire change, I think, is through positivity*. [...]. *To give people hope*. *To give people inspiration that there is another way to do this*". Consequently, she began growing mycelium, but she felt that this would need a laboratory environment. When she was looking for other ways to get involved with biodesign, she came across the roots of a willow tree underwater, while photographing a river, in 2018. This was Zena's moment of inspiration – she made the association with the mushroom roots (mycelium) and the binding properties of plant roots. Rootfull experiments followed	
MATERIALS AND PROCESSES: Wheatgrass seed was grown over hand-carved beeswax molds. After harvesting the roots were left to dry out for 24 hours. "When freshly harvested the roots are heavy and damp and after 24 hours they dry out to become featherweight, and strong enough to support their own weight" (HOLLOWAY, 2022). The same beeswax templates were reused to grow new material. Zena tells she could grow approximately 4 square meters at a time. When she wanted to change a pattern, she had to melt the beeswax to carve the new design. After drying the roots, they needed to be stabilized, because they became brittle. Zena used natural oils and waxes for conditioning the dried roots.	
PRODUCT DIMENSIONS: A long dress size	BATCH SIZE: Every piece is unique

Source: Elaborated by the author based on the interview and Zena's website (2022)

Figure 32 presents the design process model for a Rootfull dress. Each square represents a day. The project phase that took the most time was Develop, which in this project corresponded to the Conceptual Project in the PDP model. As each piece is unique and Zena does not intend to produce the dress in series, the Detailed Project and Preparation for Production phases consist of using insight and knowledge developed in this project to the next one. Zena Holloway's design process is mainly experimental and is outlined in Figure 32.

Figure 32 – Zena Holloway's dress timeline



Source: Elaborated by the author (2022)

Discover

The process began in 2018 with experimentations in growing the material: "The roots of the wheatgrass plant can be grown vertically or horizontally and follow the form of the templates they grow into. They can be forced into small spaces so they become flat and compact or encouraged to grow more deeply to create 3D shapes" (HOLLOWAY, 2022). One of the main drivers of the project is sustainability. Zena uses locally sourced and organic ingredients, she also reuses water from runoff and the material byproducts are used to feed animals (HOLLOWAY, 2022). Understanding the best way to grow the seeds took some years, until, 2021. It turns out, roots do not like to grow next to any kind of material – Zena found out that they enjoyed beeswax. She explains that, especially for man-made materials, the roots tend to recoil. She also found out that grass seeds like to grow together, they have a tendency to entangle. Seeds that grew separately did not grow as well as those that grew together. Zena photographed her process and results, taking notes on the experiments she made with conditioning and finishing agents.

With several material samples in hand, Zena bought a dress form and began her compositions. The idea of the wearables came with the thought that a better point could be made by tackling an industry that has a very harmful effect on the environment, the fashion industry. It was by developing a product that was meant to be used by people, which is intended for human reference, that Zena thought she could make a bigger impact: "[...]*all the pictures that I ever did that had people in them, were much more inspirational than photographs without. They traveled further, they got seen more* [...]".

The main concept inspiration for Zena were the corals and the marine life – it was where she originally began. According to her, this is where the message gets reinforced: "*Look what's happening with the corals and look what we are doing*". Another important reference was Alexander McQueen. With those two main conceptual guidelines, Zena did some drawings, but she mainly developed her compositions directly on the dress form: "Most honest results are achieved by working with the natural flows of the fiber. It can be grown into large hanging structures or set and molded to form vessels. It responds especially well to natural dying processes." (HOLLOWAY, 2022). Eventually, she grew more pieces to achieve the harmony she wanted for each piece.

Develop

After Zena set her vision for the dress, she adjusted it for a better fit. One of the dresses she wanted to make longer, so she tore it and grew new pieces which were later added in. She explained that radical changes to a piece are not possible once it's assembled: *"once you cut, once you do it, you haven't got that many times that you can take it".* The challenge is to compose with the material that she got: "Each growing cycle produces a different result, so no two pieces ever grow the same. The challenge is to sew, cut, tease, join, pluck, set, and reset until the root has found the optimal form" (HOLLOWAY, 2022). The results are not always what Zena expected in the beginning: "[...] *I've become to expect things not to go to plan*" (Zena).In her process, sometimes Zena prototypes until she gets the best results, like the earring shown in Table 9 She reveals that 10 or 20 were made before the final piece turned out as she wished.

Deliver

Because of the pandemic, no tests were performed on the products so far. In the near future, Zena will participate in some events to showcase her work and get the public's feedback on it.

The most challenging bottlenecks were the learning curves, about growth and how the rhythm changed in winter; and also on how to stabilize the material: "*the root is quite strong when it's dry, but when it's wet it becomes quite loose and it pulls apart easily*" (Zena). For different purposes, different consistencies of the material are needed - one of the biggest learning curves was to find out how to achieve these different consistencies.

For young designers, Zena advises: "[...] *I would just say be completely optimistic all the way and believe in what you are doing. If somebody says it can't be done, just ignore them and keep going. I think that you mustn't expect it to happen immediately, you must expect to fall ten times and get up again,* [...] *And finally, things will happen, good things will happen*[...]".

4.3.5 Design in collaboration with bacteria

Finally, the last interviewee was Breno de Abreu, he is the creator of the Biostudio project. The project focuses on teaching and developing the field of Biodesign. For this interview, Breno talked about one initiative within the project: coloring textiles with bacteria.

Specifically, the development of textile patterns colored by bacteria. Breno's background is in Biology, Design, and Art. He has been working on designs in collaboration with living organisms for 10 years.

The interview happened in June and it lasted about one hour and 40 minutes. Table 10 shows the project summary.

Table 10 –Biostudio's project summary

Source: Abreu (2015, pp.116-7)

PROJECT NAME: Biostudio	
YEAR: 2013	DEVELOPMENT DURATION: 15 months (without considering the writing of the master's thesis)
BRIEFING OVERVIEW : The project was developed in the context of Breno's master thesis project, where he had some research questions he had to answer. The project foresaw a target audience that tends to prefer natural things, cares for the quality of life and comfort, and likes to cook their own food and eat organically. For this reason, one goal was to work with natural textiles. He did not want the project to be an industrial endeavor, but a	

Table continues next page

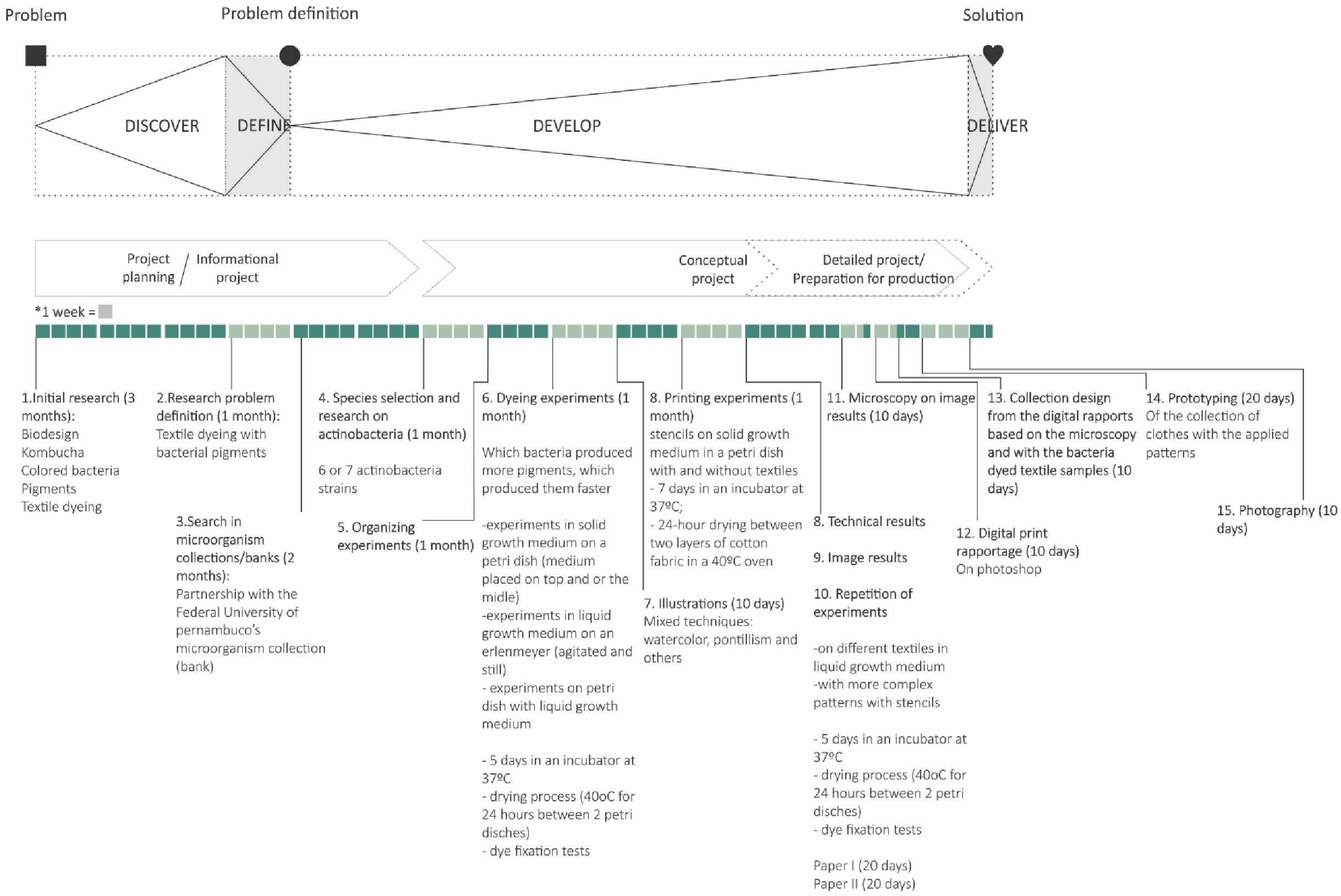
Table 10 –Biostudio's project summary

handcrafted one, maybe even a do-it-yourself kit for users to try to color their clothes themselves at home. The end result has a more stained and artisanal look, which agrees with the expected target audience. There was no budget for the project, Breno formed a partnership with the Federal University of Pernambuco, using their laboratory infrastructure. He paid for small supplies like single-use Petri dishes himself. According to him, prototyping was the biggest cost. A project constraint was the time Breno had available in the lab. He tried to do some experiments at home, but there he had no access to agitators or proper equipment.	
MATERIALS AND PROCESSES: Cotton, flax and silk, Petri dishes, growing medium, oat bran, stencils.	
PRODUCT DIMENSIONS: Textile samples wit 12 cm diameter or 20 cm in diameter, applied on shirts.	BATCH SIZE: 2 prototypes and many test samples

Source: Elaborated by the author based on the interview (2023)

Figure 33 presents Breno's design process model for the textile patterns with pigments grown by bacteria. Each square represents a week. Again the Develop phase seemed to be the longest of the project. Compared to the PDP model, the Develop phase contains part of the informational project, the Conceptual project, and the Detailed Project/Preparation for production.

Figure 33 – Breno de Abreu's bacteria patterns timeline



Source: Elaborated by the author (2022)

Discover

The project did not begin with an application in mind, the main orientation was to develop the use of bacterial pigments on textiles. The application came at a later stage, based on Breno's previous professional experience in fashion. Two main references inspired the project: designer Suzane Lee's Biocouture and a collection by Maison Martin Margiela treated with molds and bacteria. Lee developed clothing pieces of bacterial cellulose grown from Kombucha, while Margiela developed a prototype of a mannequin in which bacteria grew onto, coloring the fabric in the process. Those were to be considered "similar" projects at the time.

Breno noticed the rise of a group that cares for sustainability and worries about the environment – this became the main background motivation for the project.

The research for the concept was based on Breno's artistic drawing process. He teaches students to draw, hence this is very intense in his own process. He drew the microorganisms into the project's moodboards (Figure 34), mixing geometric and organic forms. He reflected a lot on the form of the bacteria, which is spiral, and the shapes it makes while growing. He was also inspired by the fabric fibers forming the textile. The fibers have a connection to the plants, which also have a connection to the studied bacteria, which has a symbiotic relation to plant roots – those ideas were also included in the moodboards. Watercolor was one of the techniques in the drawings, which helped to give a stained look, the same look bacteria had made on the first tests Breno conducted over textiles. The logo of the project, Biostudio, was also inspired by these moodboards.

Figure 34 – Breno de Abreu's moodboards

Source: Abreu (2015, pp.111-2)

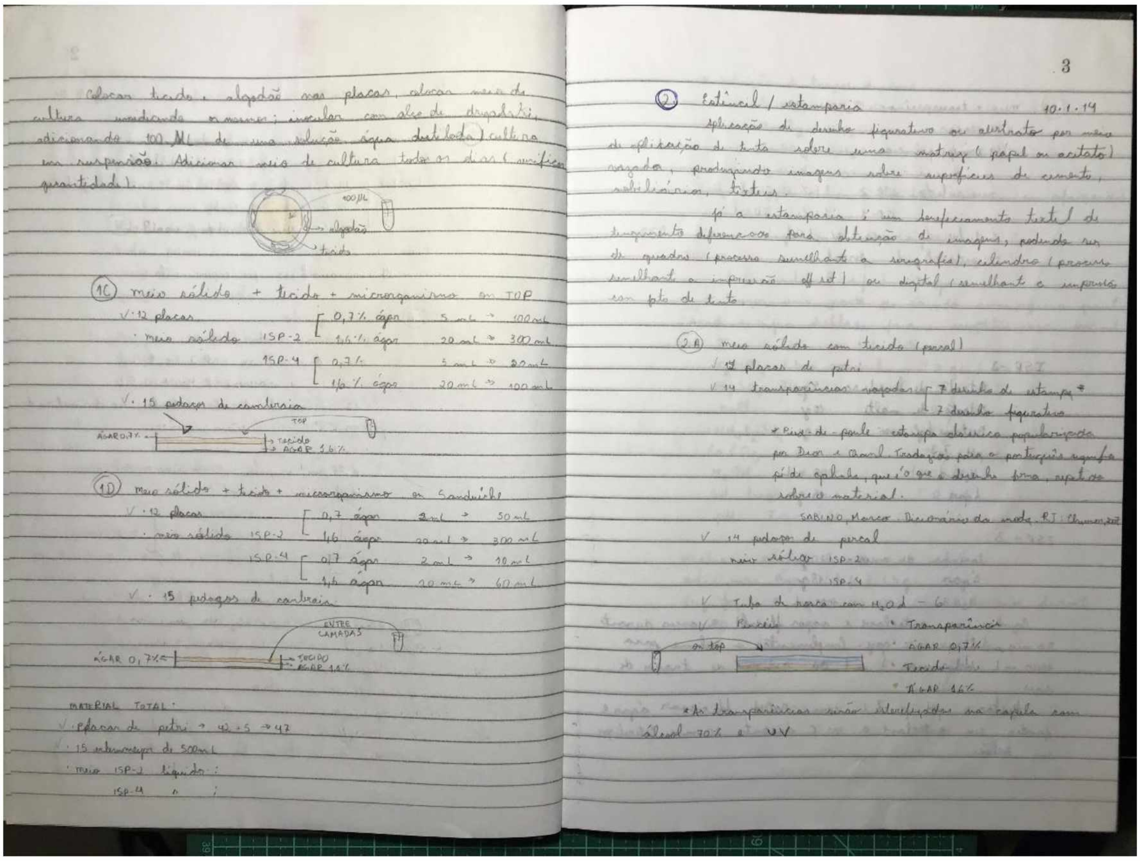
Regarding trend research, one of the main references was William Myers' book (MYERS, 2018) – which inspired ideas about the process and final product. In his courses as a professor in a fashion design program, Breno and his students had found at the time a trend of bioinspiration. So this has influenced him indirectly in the creative process.

Many bioart projects were part of the research, like Eduardo Kac – but Breno did not want to get into the ethical discussions.

Define

The first tests were conducted at the Federal University of Pernambuco, and they were registered in a laboratory journal (Figure 35). Breno explained that he and his advisor, Glaucia, made diagrams and drew schemes of the experiments they wanted to perform in this journal, listing the experiments along the materials.

Figure 35 – Breno de Abreu's lab journal



Source: Image courtesy of Breno de Abreu (2022)

He has developed a scheme to organize the experiments: (1.1) experiments in solid growth medium on a Petri dish (growing medium placed on top and or the middle); (1.2) experiments in liquid growth medium on an Erlenmeyer (agitated and still); (1.3) experiments on a Petri dish with liquid growth medium. The samples were kept for 5 days in an incubator at 37ºC. The textiles were dried at 40ºC for 24 hours between 2 Petri dishes. Breno also conducted dye fixation tests. Six or seven different strains of the same bacteria were tested, delivering different colors. The selection of the best results was done visually according to the criteria: which strain produced the most pigments and which bacteria produced pigments faster.

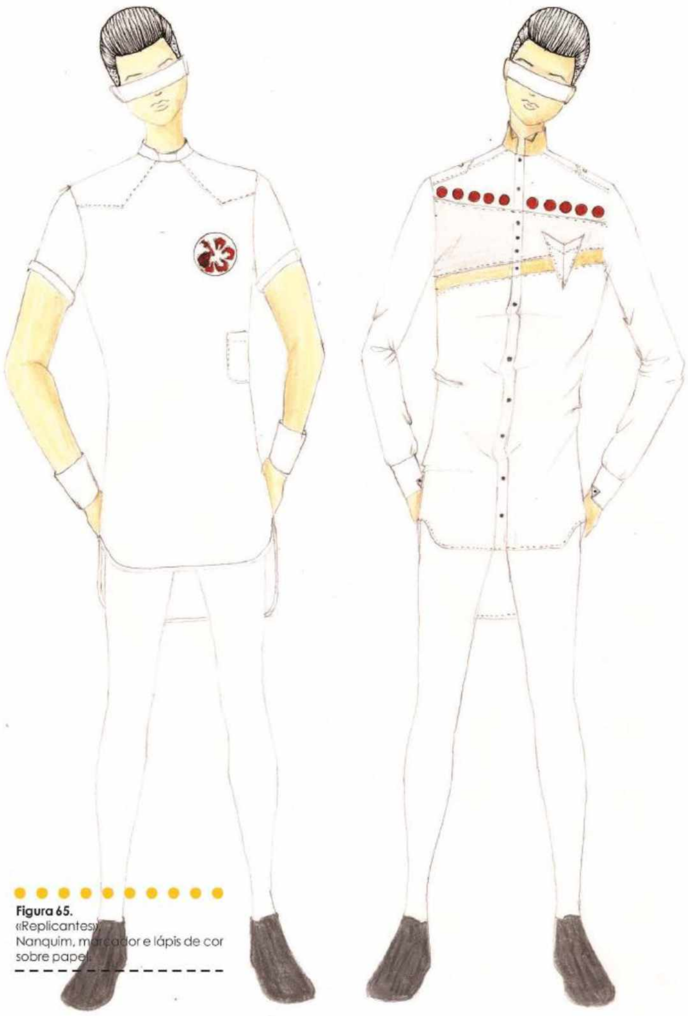
Develop

The best results were taken to the next phase, which was tests with prints: (2.1) stencils on solid growth medium in a Petri dish with and without textiles, 7 days in an incubator at 37ºC. Some of the tests were repeated: (3.1) on different textiles in liquid growth medium; (3.2) with more complex patterns with stencils. Again the samples stayed 5 days in an incubator at 37ºC and the drying process consisted of laying them at 40ºC for 24 hours between 2 Petri dishes. Additionally, dye fixation tests were made with the new samples.

To better display the bacteria prints, Breno developed a collection of clothes. The concepts of the collection were based on the moodboard, adding some new references to the mix. The Blade Runner movie and its replicants were an important reference. Breno also mixed regional themes, like the Mandacaru flower, which originated in the same geographical region that the bacteria, the Brazilian Caatinga. Additionally, for the prints, he was inspired by psychological test imagery, because people tended to try to look for figures on the bacteria tests. Breno explains that he did not want to look at too many external references at the beginning of the project, so it could begin more broadly – the references were incorporated along the project. The association Breno made with the movie relates to the bacteria as replicants: one cell produces many clones.

With all test samples in hand, he began sketching the collection, looking for the product mix. For the collection, he wanted a mix of sporty clothes and tailored cuts, focusing on the concept of comfort. The collection (shown in Figure 36) has a futuristic look, predominantly in white.

Figure 36 – Breno de Abreu’s concept sketches



Source: Abreu (2015, p.115)

Prototyping was done by a tailor. Breno was consulted during the process, especially for the application of the prints. “*As I was doing small samples, I was applying them to the pieces. So I made cotton shirts, took the bacteria-printed samples, cut them, and made an application - as if they were embroidery.* [...] *So, there is a shirt that has a pocket with the pattern* [for example]”.

In the beginning, Breno imagined he would achieve uniform colors with the bacteria, and he imagined an industrial silkscreen process. Through experimentation, he realized this would not be possible and the solution was the applied prints.

Softwares used in the process were Photoshop, for rapporting, and the microscope’s embedded software for photography.

Deliver

With regards to tests made along the design process, Breno explained that he had already preliminary data about the bacteria provided by the Federal University at the beginning of the project - like the bacteria's DNA sequence, which allowed him to identify the exact strain the bacteria pertained to. He also knew the bacteria was not pathogenic. Now the samples were submitted to tests of "*chromatography to actually see what the pigment is; solidity analysis; washing; colorimetry, to know exactly what shades are being applied*" (Breno). These tests were outsourced. Regarding product user research, no tests were conducted yet because of the experimental character of the project.

When asked what he would have done differently, Breno tells he would have investigated more natural dying processes and textile technologies: "*If I knew better the specificity of pigment types, how they bind to the fiber, maybe I would have worked more with yarn than with fabric, because the finished fabric goes through many finishing processes, it is no longer a virgin yarn that receives pigmentation much better*" (Breno). On the other hand, he evaluates that not knowing all about the technology previously brought more unexpected and less restrained results. Now the process is changed: the bacteria are cultivated without the fabric, are centrifuged, and the fabric is pigmented afterward, in an open environment. This optimized the process, allowing bigger quantities to be produced.

The main bottleneck of the project was the infrastructure and the lack of an easily available laboratory.

Teamwork happened all over the project: with Breno's supervisor at the University of Brasilia; his co-supervisor at the Federal University of Pernambuco, the laboratory technicians and other students working at the lab; other professors of his post-graduate program at the time; and with two tailors and one pattern maker.

When asked what changed in his design process since he began working with design with other living organisms, Breno tells that the way he develops what he called "Pre-project" changed. The "Pre-project" would correspond to the Define or Project Planning phase. According to him, the initial project goal is more open to experimentation and not so much problem-solving oriented: "*to have a more sensorial look at the various possibilities that the artifact or product can represent. And from the moment we get the first results, there are different interpretations of them* [...] other than *what the user wants, what else can we extract* *from these results?* [...] *to have something more poetic, and also to make other associations to those results, with cultural and historical meanings.* [...] *it is not only a product, but it can* [...] *occupy other stories. I have made many more connections with the results I am getting, the way of talking about the product is dıfferent"* (Breno).

Breno's advice for young designers who wish to work in collaboration with living organisms is to accept that control is limited and, in the end, it comes much more to observation than control. "*But that we can see things in a broader way and often through the eyes of others".* When it comes to validation, Breno recommends a broader look at the opinions of others rather than right or wrong, to keep an open mind to different views about the subject.

4.4 THE FRAMEWORK

The development of the framework began with the analysis of the related artifacts listed in section 4.2 and the insights which were inspired by them. There are 59 insights and some of them intersect with each other.

Insights were analyzed along with the pedagogical foundations developed by Charlotte Sörensen (2018) - thus laying the background for 17 requirements to be considered in the framework design (section 4.4.2). This answers objective O3 – "To define the requirements for the teaching and learning facilitating artifact". Not all insights yielded framework requirements, but they were used to orient the framework's development in many aspects, like the use of specific tools, certain concepts, and contents to be added to the repertoire and theory of the application script, and some practical ideas. Following the underlining of the framework's requirements, learning objectives were designed according to Bloom's Taxonomy. Each objective drew on one or more requirements.

Based on the learning objectives and framework's requirements, the framework was designed considering two different learning contexts: the student's homes and the classroom. Each activity was developed and described and materiality elements for the framework were also proposed. This addresses objective O4- "To formulate the framework for teaching and learning structure and elements".

Finally, an evaluation rubric for the framework was developed, guided by the learning objectives. This answers objective O5- "To establish an evaluation rubric for the proposed framework and its outcomes”. The rubric was later used for students and the course professor to rate their perceived learning results.

The complete method for the framework’s development has been previously detailed in section 3.4 and the next sections describe the results beginning with the pedagogical foundations, following the framework’s requirements, learning objectives, the description of the framework for teaching and learning the biodesign process, finishing with the description of the evaluation rubric for the framework.

4.4.1 Pedagogical foundations

To develop the framework, it was important to first look into well-established pedagogical design theories, principles, and practices. There is already a whole section (2.6) that looks into teaching and learning design in collaboration with other living organisms. Despite the great amount of information, there were no pedagogical foundations retrieved in the sample of sources that was looked into. To look for a pedagogical foundation reference, one logical path seemed to be the teaching and learning of materials in design. This seemed where teaching design in collaboration with other living organisms seemed to be most commonly placed for now – hence often called “design with living materials” (CAMERE; KARANA, 2018). For this reason, this study turned to Charlotte Sörensen’s “Material Framework for Product Design. The development of reflective material practices” published in 2018. Her framework was “designed to facilitate the development of reflective material practices in design education” (SÖRENSEN, 2018, p.8) and is comprised of four levels, being the first “a pedagogical foundation based on Experiential Learning theory that provides a framework for how to approach teaching and learning” (SÖRENSEN, 2018, p.8). Figure 37 shows an overview of her framework and its levels.

Figure 37 – Charlotte Sörense's framework

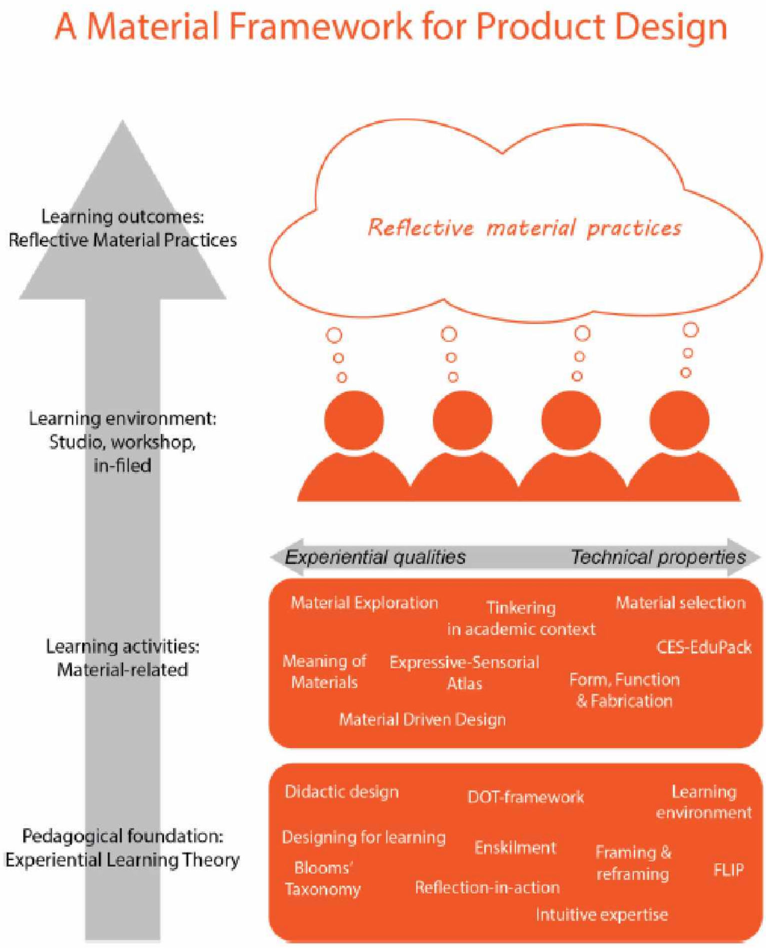


Figure 23 The pedagogic model A Material Framework for Product Design is designed to facilitate the development of reflective material practices in design education.
The Framework consist of four levels: (1) a pedagogical foundation based on Experiential Learning theory that provide a framework for how to approach teaching and learning, (2) designing and structuring learning activities, (3) creating learning environments that facilitate learning activities, and (4) defining learning objectives, assessment of learning outcomes and detecting signs of learning.

Source: Sörensen (2018, p.64).

For practical purposes, the insights that followed Sörensen's framework were included in Table 5, in section 4.2. Some of them were later considered to build the teaching and learning biodesign framework's requirements. They include:

- Experiential learning: "Experiential Learning Theory builds on a philosophy of education, based the work of Kurt Lewin, Jean Piaget and what John Dewey, originally called a theory of experience (Dewey, 1938) or 'learning-by-doing'" (SORENSEN, 2018, p.21);
- Reflection-in-action: The learning-by-doing leads to a reflection-in-action posture by the teacher and the students (SORENSEN, 2018);

- The use of Bloom's taxonomy for underlining the learning objectives;
- The thinking about creating learning environments and assessment of learning signs – Sörensen points out that the different learning environments trigger different roles in students, rendering them more proactive or more passive (2018);
- Open-ended assignments, like a project: "[...]to reach a meta-cognitive knowledge level it is necessary to create assignments that are open and complex enough to allow the students to continue to elaborate [...]"(SORENSEN, 2018, p.25);
- To favor examples over rules: "The 'triangulation first' pedagogy favours examples over rules, and open-ended problems combined with student-defined questions, which stimulate students to solve research problems using individual approaches" (SORENSEN, 2018, p.29).
- The use of existing design kits, like the Ma2E4 toolkit (CAMERE; KARANA, 2018b);
- Structured exercises: "[...] less experienced students at bachelor level need clear guidance. The guidance could be a mixture of regular seminars, logbooks and guides designed to support different stages of the explorative process" (SORENSEN, 2018, p.70).
- Tinkering, as explained in section 2.5.10;
- To help students reframe according to the context: "By posing questions instead of giving answers stimulates the students' reflection and reframing. [...]" (SORENSEN, 2018, pp.52-53). According to Sörensen, "Frames are defined by the methods a designer selects to apply in a given process or a specific project. The frames offer a structure to deal with unfamiliar territories and over time, the reinforced practice contributes to the development of intuitive expertise" (2018, p. 30).

This list compiled the pedagogical foundations, which along with the insights, resulted in the framework's requirements.

4.4.2 Framework requirements

Framework's requirements were based on the insights and on Charlotte Sörensen's proposed pedagogical foundations. Insights no. 5, 9, 10, 12, 17, 18, 43, 46, 47, 49, 50, 51, 54, and 58 (listed according to Table 5) were not taken into consideration because of the time and resource limitations in this study – or not to restrain the framework too much. This will be further addressed in the Discussion chapter of this thesis. The requirements are presented below with each insight (referenced by number according to Table 5):

1. The framework needs to offer the students laboratory experience even without having real access to a laboratory (13, 23, 27, 33, 34, 40, 41, 45, partially 52);
2. The framework needs to guide the building of a repertoire in biodesign concepts and case studies, giving preference to examples rather than theory (2, 8, 20, 22, 32, 33, 39, 42, 57);
3. The framework should make space for reflections about the differences and specificities in the biodesign process (3, 6, 7, 15, 27, 31, 38, 39);
4. The framework needs to follow the pedagogical foundation of "Learning by doing" (13, 23, 27, 33, 40, partially 52);
5. The framework has to include materialities that guide and help students to control their own design processes, for example, a project journal (15, 19, 23, 27, 29, 33, 35);
6. The framework needs to consider the "Technology Readiness Level" and guide students to develop their projects considering feasibility and marketing (19, 21, 23, 48, 55);
7. The framework needs to help students to develop empathy toward the organism participating in the project (1, 4, 32, 56);
8. The framework should address ethical considerations (4, partially 37);
9. The framework has to foresee the possibility of in-action feedback (33, 41, partially 44, partially 59);

10. The framework has to consider the possibility of the insertion of interdisciplinary feedback (partially 11, 30, partially 44, partially 53, partially 59);
11. The framework needs to address representation issues in the design process (14);
12. The framework needs to help students to think in 4 dimensions and to manage time (15, 19, 24, 38);
13. There should be space in the framework to make students comfortable with specific vocabulary and scientific papers (25, 32, 39);
14. The framework should guide students to think on an experiential level, rather than only technical qualities – to address a more fitted product application (26, 28, 33);
15. The framework needs to help students to address costs, value, and market placement (19, 24, 48, 55);
16. The framework should facilitate the student's reframing process across the project development (33);
17. The framework needs to try to reduce complexity (36).

The requirements are not ranked and are considered to be equally relevant to the framework. The next section describes how the requirements led to the learning objectives for the framework.

4.4.3 Learning Objectives

To guide the design of the framework for facilitating the teaching and learning of design in collaboration with other living organisms, 21 learning objectives were formulated based on the framework's requirements. To formulate them, Bloom's Taxonomy was used to guide the process (ERASMUS UNIVERSITY ROTTERDAM; 2023). Table 11 shows the learning objectives and how the requirements relate to them.

Table 11 –Requirements and Learning Objectives

Requirements	Learning Objective
2. The framework needs to guide the building of a repertoire in biodesign concepts and case studies, giving preference to examples rather than theory; 13. There should be space in the framework to make students comfortable with specific vocabulary and scientific papers; 17. The framework needs to try to reduce complexity;	(Understand) The students should be able to understand biodesign concepts and recognize them in the future;
2. The framework needs to guide the building of a repertoire in biodesign concepts and case studies, giving preference to examples rather than theory; 17. The framework needs to try to reduce complexity;	(Analyze) Based on an initial given repertoire, the student should be able to link biodesign projects to existing biodesign frameworks;
2. The framework needs to guide the building of a repertoire in biodesign concepts and case studies, giving preference to examples rather than theory; 7. The framework needs to help students to develop empathy toward the organism participating in the project; 8. The framework should address ethical considerations;	(Evaluate) The student should get to know the main ethical reflections in biodesign and exercise empathy with other living beings;
4. The framework needs to follow the pedagogical foundation of "Learning by doing"; 16. The framework should facilitate the student's reframing process across the project development; 17. The framework needs to try to reduce complexity;	(Create) Articulating the initial repertoire presented in class, the student should be able to formulate their own initial ideas for a biodesign project to be developed in the course (with mycelium composite);
2. The framework needs to guide the building of a repertoire in biodesign concepts and case studies, giving preference to examples rather than theory; 13. There should be space in the framework to make students comfortable with specific vocabulary and scientific papers; 17. The framework needs to try to reduce complexity;	(Apply) Using database tools, such as Google Scholar, Web of Science, and others, students should be able to select relevant scientific material for the project they will develop, summarizing important information;
3. The framework should make space for reflections about the differences and specificities in the biodesign process; 16. The framework should facilitate the student's reframing process across the project development;	(Apply / create) Students should be able to take into consideration the particularities of design in collaboration with living organisms in the project that they develop in the course and in their own design practices;
14. The framework should guide students to think on an experiential level, rather than only technical qualities – to address a more fitted product application; 16. To help students in the reframing process across the project's development; 17. The framework needs to try to reduce complexity;	(Evaluate) Based on the MA2E4 method applied in the classroom, students should be able to evaluate and characterize materials in a sensorial, performative, affective, and interpretative dimension – aiming the creation of a vision for the project they are developing in the course, with the facilitation of a vocabulary;

Table continues next page

Table 11 –Requirements and Learning Objectives

Requirements	Learning Objective
2. The framework needs to guide the building of a repertoire in biodesign concepts and case studies, giving preference to examples rather than theory; 5. The framework has to include materialities that guide and help students to control their own design processes, for example, a project journal; 7. The framework needs to help students to develop empathy toward the organism participating in the project; 13. There should be space to make students comfortable with specific vocabulary and scientific papers; 17. The framework needs to try to reduce complexity;	(Understand) Students should get to know the organism they are working with in order to develop empathy and stimulate the assimilation of operational vocabulary of the biological sciences;
4. The framework needs to follow the pedagogical foundation of "Learning by doing"; 16. To help students in the reframing process across the project's development;	(Create) Participating in the proposed dynamics, students should be able to generate ideas of possibilities of product applications by market segmentation, ideas of themes, ideas of processes for their projects;
4. The framework needs to follow the pedagogical foundation of "Learning by doing"; 14. The framework should guide students to think on an experiential level, rather than only technical qualities – to address a more fitted product application; 16. The framework should facilitate the student's reframing process across the project development; 17. The framework needs to try to reduce complexity;	(Evaluate) Practicing the tools proposed in class, students should be able to develop autonomy to make decisions about a product application of the material and a product vision for their projects;
1. The framework needs to offer the students laboratory experience even without having real access to a laboratory; 4. The framework needs to follow the pedagogical foundation of "Learning by doing"; 5. The framework has to include materialities that guide and help students to control their own design processes, for example, a project journal; 16. The framework should facilitate the student's reframing process across the project development; 17. The framework needs to try to reduce complexity;	(Apply / create) Based on the ideas generated in the class brainwriting, on the repertoire presented in class, and on the previous readings, the students should feel able to develop out-of-class experiments (tinkering) and record them in the project journal in a structured manner;
1. The framework needs to offer the students laboratory experience even without having real access to a laboratory; 3. The framework should make space to reflections about the differences and specificities in the biodesign process;	(Analyze / evaluate) Developing their sensibilities in working with other living organisms, students should be able to identify variables that impact the final outcome of their projects by tracking the variables, such as the environmental conditions;

Table continues next page

Table 11 –Requirements and Learning Objectives

Requirements	Learning Objective
4. The framework needs to follow the pedagogical foundation of "Learning by doing"; 5. The framework has to include materialities that guide and help students to control their own design processes, for example, a project journal; 12. The framework needs to help students think in 4 dimensions and manage time; 16. The framework should facilitate the student's reframing process across the project development; 17. The framework needs to try to reduce complexity;	
4. The framework needs to follow the pedagogical foundation of "Learning by doing"; 6. The framework needs to consider the "Technology Readiness Level" and guide students to develop their projects considering feasibility and marketing; 15. The framework needs to help students to address costs, value, and market placement; 16. The framework should facilitate the student's reframing process across the project development;	(Evaluate) Practicing the tools proposed in class, students should be able to develop autonomy to make decisions on strategic market positioning and price positioning for their projects;
4. The framework needs to follow the pedagogical foundation of "Learning by doing"; 16. The framework should facilitate the student's reframing process across the project development;	(Create) Based on the previous information and exercises, students should be able to develop design alternatives for their projects;
1. The framework needs to offer the students laboratory experience even without having real access to a laboratory; 5. The framework has to include materialities that guide and help students to control their own design processes, for example, a project journal;	(Understand) Students will understand the process of developing the mycelium composite raw material in a domestic (non-laboratory) context so that if desired, they can produce it independently;
4. The framework needs to follow the pedagogical foundation of "Learning by doing"; 9. The framework has to foresee the possibility of in-action feedback; 16. The framework should facilitate the student's reframing process across the project development; 17. The framework needs to try to reduce complexity;	(Create) Consolidate a concise communication of the ongoing project, in order to move toward its realization;
9. The framework has to foresee the possibility of in-action feedback; 10. The framework has to consider the possibility of the insertion of interdisciplinary feedback;	(Understand) Students should be able to identify possibilities for improvement in the project based on received feedback;

Table continues next page

Table 11 –Requirements and Learning Objectives

Requirements	Learning Objective
16. The framework should facilitate the student's reframing process across the project development;	
11. The framework needs to address representation issues in the design process;	(Understand) Students should get to know the dynamics of one of the main digital representation tools used in the practice of design with living organisms;
5. The framework has to include materialities that guide and help students to control their own design processes, for example, a project journal; 6. The framework needs to consider the "Technology Readiness Level" and guide students to develop their projects considering feasibility and marketing; 15. The framework needs to help students to address costs, value, and market placement; 16. The framework should facilitate the student's reframing process across the project development; 17. The framework needs to try to reduce complexity;	(Apply/ analyze) Reflecting on the pricing of the product, students should be able to reassess the initial strategy established for the project and readjust it if necessary;
5. The framework has to include materialities that guide and help students to control their own design processes, for example, a project journal; 12. The framework needs to help students think in 4 dimensions and manage time; 16. The framework should facilitate the student's reframing process across the project development; 17. The framework needs to try to reduce complexity;	(Apply/analyze) Students should be able to reflect on the project management, comparing the planned timeline to the executed timeline;
6. The framework needs to consider the "Technology Readiness Level" and guide students to develop their projects considering feasibility and marketing; 15. The framework needs to help students to address costs, value, and market placement;	(Create) Students should be able to develop a communication piece for the product's promotion.

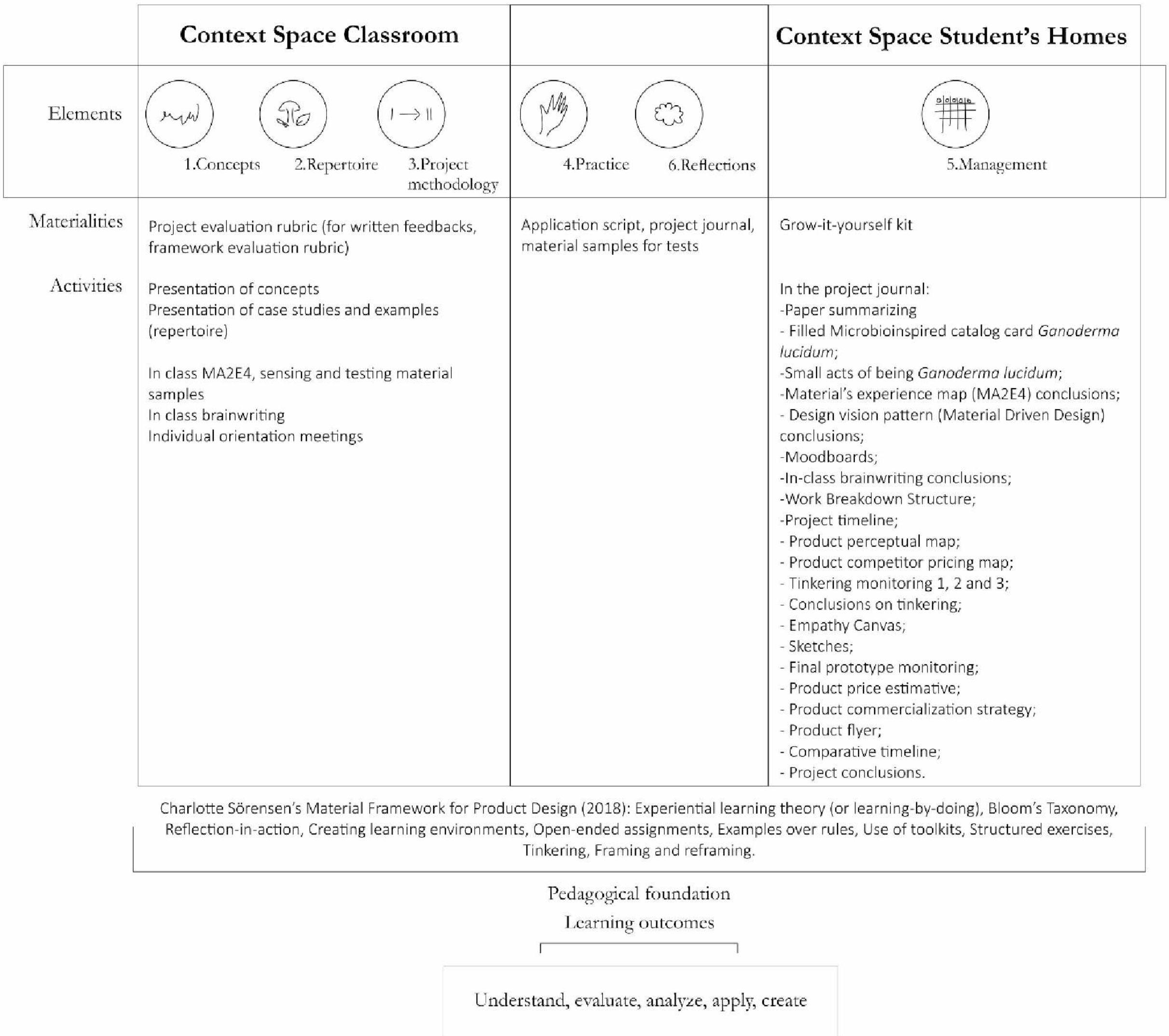
Source: Elaborated by the author (2023)

The learning objectives were used as the guidelines to organize the activities within the framework and also to later conduct its evaluation.

4.4.4 Framework for teaching and learning design in collaboration with other living organisms

Figure 38 presents a schematic of the framework. It is organized in two main context spaces: (I) the classroom and (II) the student's homes. It is constituted of 6 main elements: (1) Concepts; (2) Repertoire; (3) Project methodology; (4) Practice; (5) Management; and (6) Reflections. The materialities in the framework are a framework application script, a project journal, material samples for tests, a grow-it-yourself kit, a project evaluation rubric (for written feedback for the students), and the framework's evaluation rubric. Activities consist of presentations of concepts and case studies (the developed biodesign process models); the use of the MA2E4 toolkit; in-class brainwriting; orientation meetings, and activities in the project journal. The whole structure is supported by the pedagogical foundations according to Charlotte Sörensen's framework. Finally, the learning outcomes are the learning objectives. The context spaces, elements, materialities and activities are better detailed in the next sections.

Figure 38 – Framework for teaching and learning design in collaboration with other living organisms



Source: Elaborated by the author (2022)

Context space (1) classroom refers to the classroom itself. At the Federal University of Paraná, it assumes the configuration of tables and chairs for the students on one side, and the lecturer standing on the opposite side. It can also assume the setting of an auditorium, such as shown in Figure 39. A blackboard and a light projector are available. The other context space is the (2) students' homes. The tinkering and experimentation activities happen in the students' kitchens and they develop other project activities such as sketching in their domestic environments. Some activity happens at the intersection of those two spaces. This organization enables experimentation even without the availability of a laboratory, and addresses the first design requirement: 1. The framework needs to offer laboratory experience without having access to a laboratory.

Figure 39 – Context-space classroom

Source: Elaborated by the author (2022)

Figure 40 gives an idea of what is encompassed in each of the framework's six elements. First, there is a repertoire of (1) Concepts to be explained to the students: these concepts can help them navigate important keywords, which makes it easier for them to later look for journal papers and information available. In addition to a repertoire of concepts, there is a (2) Repertoire of examples, case studies, the biodesign models previously developed, and (3) Project methodology. At this point, examples and case studies are presented (as well as the developed design process models), as well as the existing methods for designing in collaboration with other living organisms. The fourth element is (4) Practice, which is covered with activities developed in the classroom and in the student's homes – the highlights are a project and tinkering exercises with material samples and a grow-it-yourself kit. The fifth element is (5) Management, where students are encouraged to manage their own projects with the aid of a mandatory structured project journal, project presentations, and receiving feedback. Finally, (6) Reflections are made throughout the process: about ethics in designing with other living organisms, about empathy, about the project itself. The project development and the journal run through the four last elements.

Figure 40 – Framework's elements

1.Concepts

Biodesign (MYERS, 2018; COLLET, 2020)
Bionics (IOUGUINA et al., 2004)
Biomimicry (BENYUS, 2002; IOUGUINA et al., 2004)
Biomimetics (IOUGUINA et al., 2004)

Material Ecology and Templating (MOGAS-SOLDEVILLA et al., 2015; OXMAN, 2015; BADER et al., 2016; MOSER et al., 2019; SMITH et al., 2020)
Growing Design (PARISI; ROGNOLI; AYALA-GARCIA, 2016; PARISI; ROGNOLI, 2017; CAMERE; KARANA, 2018a; KARANA et al., 2018; ZHOU et al., 2020)
Epigenetics (SABIN; JONES, 2018; DADE-ROBERTSON, 2021)
Top-Down and Bottom Up (SABIN; JONES, 2018; DADE-ROBERTSON, 2021)

Characteristics of a biodesigned artifact (PARISI; ROGNOLI; AYALA-GARCIA, 2016; ; KEUNE, 2017; CAMERE; KARANA, 2018a; KARANA et al., 2018)

Camere and Karana's framework (2017)
Collet's framework (2016)
Collet's framework (2020)
Dade-Robertson's framework (2021b)

2.Repertoire

Classifications (MADIGAN et al., 2021)
Animals
Fungi
Plants
Algi
Slime Molds
Bacteria

Design process models

Who is *Ganoderma lucidum*?

How to prepare liquid culture, spawn, substrate (TANG; ZHONG, 2004; THOMPSON; THOMPSON, 2012; CULTIVE COGUMELOS, 2022; FERNANDES, 2022; TEACH GENETICS, 2022)

Agile and scrum (PMI; AGILE ALLIANCE, 2017; SUTHERLAND; SUTHERLAND, 2019)
Biodesign representation (OXMAN, 2010; OXMAN, 2014; KIRDÖK et al.,2019; ZHOU et al., 2020;HBBE 2021)
Living Systems Lab Design Process (UAL, 2022; DINIZ, 2020b)
Microbioinspired method (ABREU, 2019)
Material Driven Design (PARISI; ROGNOLI; AYALA-GARCIA, 2016; PARISI; ROGNOLI, 2017; CAMERE; KARANA, 2018a; KARANA et al., 2018; ZHOU et al., 2020)

3.Project methodology

About biodesigning (ZOLOTOVSKY, 2012; KERA, 2014; COLLET, 2017; KEUNE, 2017; CAMERE; KARANA, 2018a; DEW; ROSNER, 2018; KARANA et al. 2018; DAMSIN, 2019; VETTIER, 2019; COLLET, 2020; PASOLD, 2020; DADE-ROBERTSON, 2021a)

Design process models

4.Practice

Grow-it-yourself kit (MONNA, 2017; PARISI; ROGNOLI; AYALA-GARCIA, 2016; PARISI; ROGNOLI, 2017)

In-class MA2E4, sensing and testing material samples (CAMERE;KARANA, 2018b)
In class brainwriting

Individual orientation meetings (teams)

5.Management

Project presentations and feedbacks (Biodesign Challenge evaluation rubric)

6.Reflections

Technology Readiness Level (DADE ROBERTSON, 2021a)
Small acts of Being (BARNETT, 2020)

About the alterity of other living beings (MANCUSO, 2019)
On the difference on what lives (DADE ROBERTSON, 2021a)
On genetically modifying (DADE ROBERTSON, 2021a)
On the energy dispended on being (VETTIER, 2019, citing Tristan Garcia)
On the right to control life (VETTIER, 2019)
On property upon life (GINSBERG et al., 2014)

Project
Project Journal (KARANA et al., 2018; SÖRENSEN; THYNI, 2021)
-Paper summarizing;
- Microbioinspired catalog card *Ganoderma lucidum* (ABREU, 2019);
-Small acts of being *Ganoderma lucidum* (BARNETT, 2020);
-Material's experience map (MA2E4) conclusions (CAMERE;KARANA, 2018b);
- Design vision pattern (Material Driven Design) conclusions (PARISI; ROGNOLI; AYALA-GARCIA, 2016; PARISI; ROGNOLI, 2017; CAMERE; KARANA, 2018a; KARANA et al., 2018; ZHOU et al., 2020);
-Moodboards;
-In-class brainwriting conclusions;
-Work Breakdown Structure;
-Project timeline;
- Product perceptual map;
- Product competitor pricing map;
- Tinkering monitoring 1, 2 and 3 ((PARISI; ROGNOLI; AYALA-GARCIA, 2016; PARISI; ROGNOLI, 2017; CAMERE; KARANA, 2018; KARANA et al., 2018; ZHOU et al., 2020) SÖRENSEN; THYNI, 2021);
- Conclusions on tinkering;
- Empathy Canvas (GRAY, 2017; GRUSHKIN, 2021);
- Sketches;
- Final prototype monitoring (SÖRENSEN; THYNI, 2021);
- Product price estimative;
- Product commercialization strategy;
- Product flyer;
- Comparative timeline;
- Project conclusions.

Source: Elaborated by the author (2022)

Concerning the framework's materialities, mycelium was described in the literature as more of a "friendly" organism for beginners who wish to collaborate in design with other living organisms (PARISI; ROGNOLI; AYALA-GARCIA, 2016; PARISI; ROGNOLI, 2017; MONNA, 2017; LAZARO VASQUEZ; VEGA, 2019; WEILER et al., 2019). For this project, a grow-it-yourself kit was prepared in partnership with the mycelium startup company NeoMatter (Figure 41). Students receive one kit to do tinkering exercises. Later, they receive the number of kits they need to prototype their final projects. The kit consists of wood sawdust (the substrate), colonized with *Ganoderma lucidum,* and an additional little bag of carboxymethylcellulose, which, with the addition of water, gives clay-like properties to the mixture.

Figure 41 – Grow-it-yourself kits for students to tinker with and develop their prototypes

Source: Elaborated by the author (2022)

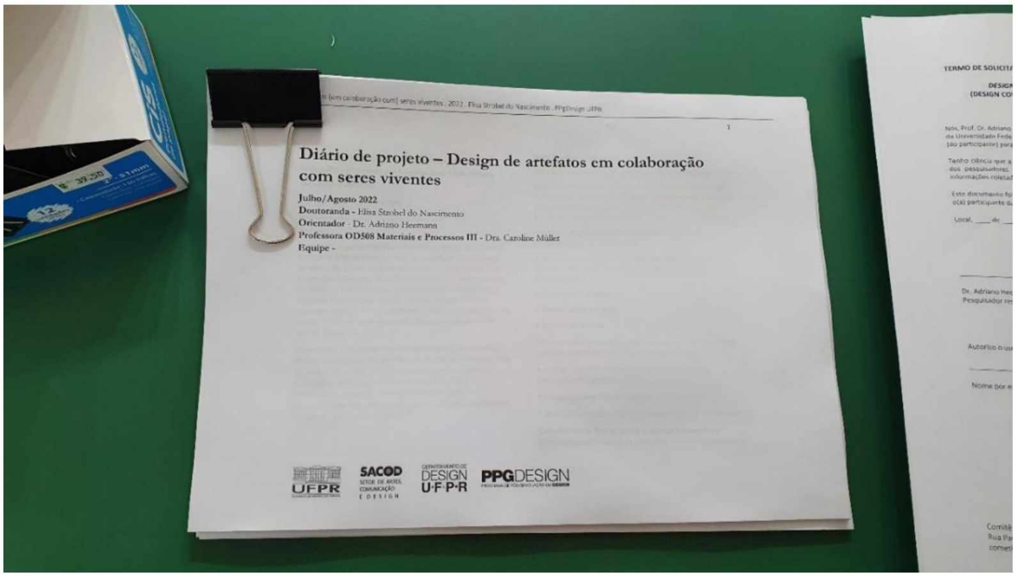
Still on the framework materialities, material samples have been provided to the students (Figure 42) by NeoMatter in order to perform tests – tinkering with finishings and understanding the material properties.

Figure 42 – Samples for students to tinker

Source: Elaborated by the author (2022)

A structured project journal (Figure 43) is also offered for each group to plan the project, write their conclusions of the activities after each class, monitor tinkering and prototyping developments, and strategically plan the product.

Figure 43 – Project journal



Source: Elaborated by the author (2022)

Table 12 presents the project journal items for an overview. Some of the items are illustrated.

Table 12 – Project journal items

1. Microbioinspired Method Catalog Card (ABREU 2019, p.25) - Prepared by Caroline Aimi Ueda Fukuda - *Ganoderma lucidum*
   [As in Figure 9, section 0]

2. "Small Acts of Being" by Heather Barnett (2020)
   2.1 Connect to this other life form and observe it attentively;
   2.2 Reflect on what it perceives, how it perceives, how it understands time;
   2.3 Reflect on what it knows about your existence and how you identify or relate to it;

3. Conclusions from the material/product experience maps (MA2E4 done in class) - draw schematically:

4. Conclusions about the design intention/vision - experience patterns: (You can put images, make schemes):

5. Moodboards (product visual expression boards):

6. Brainwriting conclusions (done in-class):
   6.1 Application ideas?
   6.2 How to do it?
   6.3 A project theme:
   6.4 Other ideas:

7. Outline the work breakdown structure (detailed activities of what needs to be done, as shown in class):

8. Draw the project timeline, as shown in class. Each little square represents one day - divide the "stages" with interventions in the timeline and drawings around them (ex: "conceptual", "informational", "need to wait for third-party production time", "time for mycelium growth", "drying", etc...):

07	07	07	07	07	07	07	07	07	07	08	08	08	08	08	08	08	08	08	08	08	08	08	08	08	08	08	08	08	08	08	08	08	08	08
21	22	23	24	26	27	28	29	30	31	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

9. Product/artifact perceptual marketing positioning (concept/values):

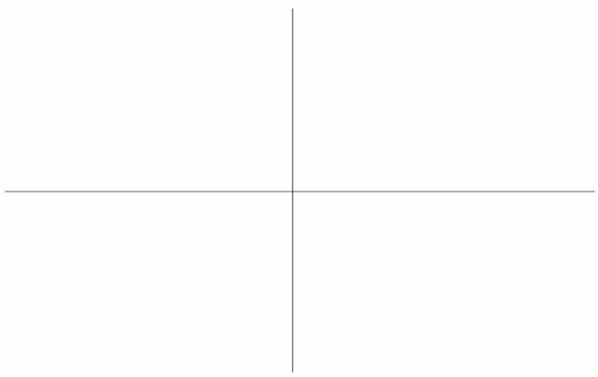


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Table 12 – Project journal items

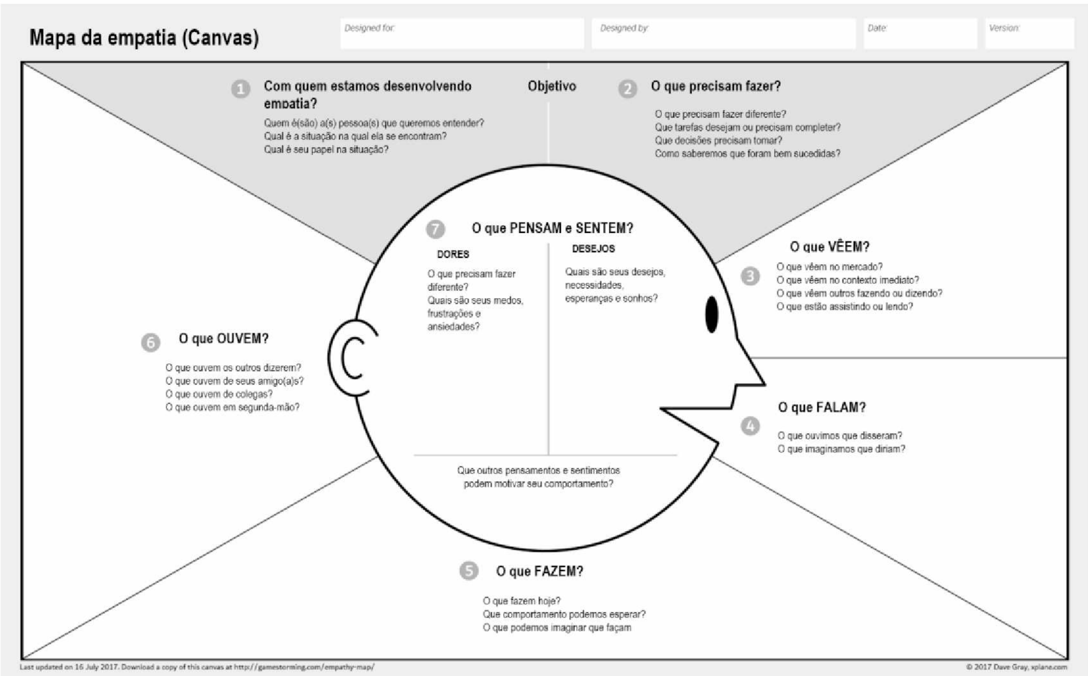
10. Product/artifact positioning (price)

R$

11. Tinkering
    11.1 Experiment 1
        Materials/Quantity/Costs
        Processes/Time/Costs
        Photographic records with process description
        Development monitoring Day's Mean temperature/Humidity/Observations
        Photographic records of development in the next 14 days
    11.2 Experiment 2
        Materials/Quantity/Costs
        Processes/Time/Costs
        Photographic records with process description
        Development monitoring Day's Mean temperature/Humidity/Observations
        Photographic records of development in the next 14 days
    11.3 Experiment 3
        Materials/Quantity/Costs
        Processes/Time/Costs
        Photographic records with process description
        Development monitoring Day's Mean temperature/Humidity/Observations
        Photographic records of development in the next 14 days

12. Conclusions of tinkering experiments (what was good, what would you do differently?):

13. Project target audience: try to think about an empathy map (model by DAVE GRAY, 2017, our translation):



14. Add here the team's drawings (at least 3 drawings with different alternatives from each member):

15. Include here the final chosen alternative represented nicely:

16. Final prototype development

Table continues next page

Table 12 – Project journal items

Materials/Quantity/Costs
Processes/Time/Costs
Photographic records with process description
Development monitoring Day's Mean temperature/Humidity/Observations
Photographic records of development in the next 14 days

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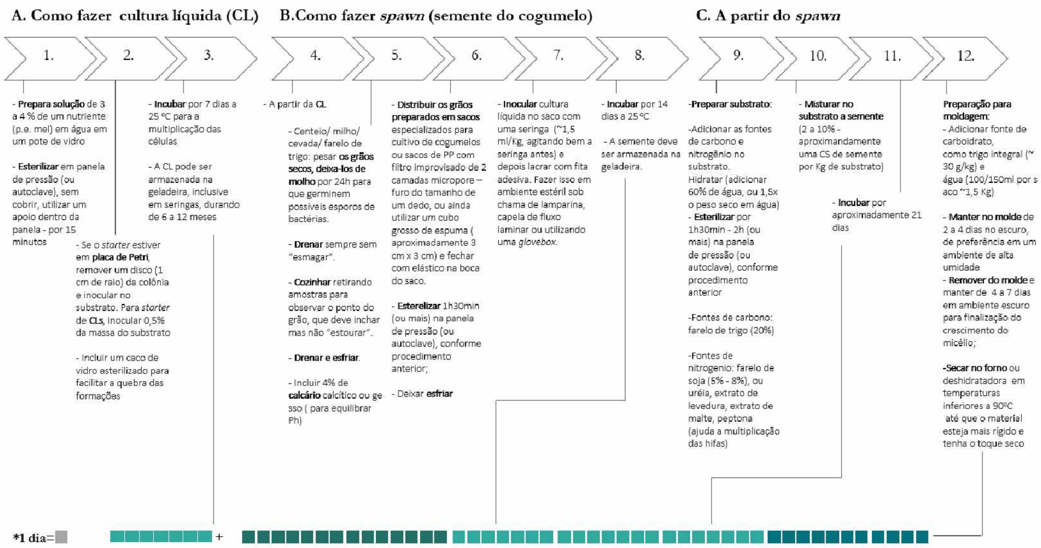
17. If you want to prepare the kit at home:



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18. Estimated cost of the final product:
Human and material resources: Quantity/Cost per unit/Total cost

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19. Reflection: hypothetically, how to achieve the commercialization of the product within the desired marketing strategy? If necessary, rethink the positioning and pricing strategy.
19.1Has anything changed in the positioning compared to what was initially proposed?
19.2What is the profit margin required for the product to fit into the value stipulated in the strategic planning?
19.3What is the size of the batch to be produced? How many units would be necessary to be sold to get a return on investment (cover development and material costs)?
19.4What could be the means of dissemination and distribution of the product?
19.5Would it be possible to expand the line? How could it be expanded?

---

20. Include here a flyer to promote the product:

---

21. Now that you have completed the project, how was the actual timeline? Compare the two:

---

22. Draw, sketch, or write down your conclusions about the project:

Glossary
[As in this document]

References
(ABREU, 2019; BADER et al., 2016; BARNETT, 2020; CAMERE; KARANA, 2018b; CULTIVE COGUMELOS, 2022; DADE-ROBERTSON, 2021a; FERNANDES, 2022; GIBNEY.; NOLAN, 2010; GRAY, 2017; KARANA et al., 2018; LI et al., 2017; LUCIA; SABIN; JONES, 2018; MOGAS-SOLDEVILA et al., 2015; MOMA, 2020; MOSER et al., 2019; NATURE PORTFOLIO, 2007; NATIONAL HUMAN GENOME RESEARCH INSTITUTE (NIH), 2022; NEEVES, 2018; OXMAN, 2015; OXMAN et al., 2015; PARISI; ROGNOLI; SONNEVELD, 2017;

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Table 12 – Project journal items

	SABIN, 2018b; SMITH et al., 2020; SORENSEN, THYNI, 2021; TANG.; ZHONG, 2004; TEACH GENETICS, 2022; THOMPSON; THOMPSON, 2012; UNIVERSITY OF ARTS LONDON (UAL), 2022)

Source: Elaborated by the author (2022)

Here, the framework is organized to fit the available research context, which is the mandatory course “Materials and Processes III”. Six modules are arranged, distributing the learning objectives and activities through them. Each module is a presential class with additional activities for the students to elaborate at home. Table 13 presents the learning objectives, the activities, and the application script.

Table 13 –Learning objectives, activities and application script

Lesson	Learning objective	Activity	Application script
1	1.1 (Understand) The students should be able to clearly associate biodesign concepts and recognize them in the future;	Presentation of the main concepts of the field - what is biodesign, its place in relation to biomimetics, tinkering, growing design, and others;	On the first day, the framework is introduced, along with the "Key Information and Consent Form to Participate in the Research Study" and the "Request for Using Image and/or Sound". A repertoire is presented on biodesign projects with animals, fungi, bacteria, and plants. Ethical aspects are discussed by Heather Barnett's "Small acts of being" exercise (2020). Biodesign concepts are presented, such as "biodesign", "material templating", "material ecology", and "emergence". Characteristics of biodesigned artifacts are explained, showing some material samples of bacterial cellulose and mycelium composites. Frameworks that organize the biodesign practices are shown to the students, explaining how some previously presented examples would fit in them. For the first external assigned activity: (I) Students are asked to organize themselves in teams with maximum of 4 participants each. (II) Each student should freely perform a desktop research, assembling a moodboard of existing mycelium products. (III) Each student should research a paper (scientific or informal developed by Grow-It-Yourself communities) and draw schematic representations of ideas of what could be done in their personal project. (IV) Each student is requested to watch a video about mycelium applications, a talk by prof. Dr. Francisco Menino Destéfanis Vítola on the Design Department`s "Prototipa Design" extension event "Conversations about Design and Living Materials" (PROTOTIPA DESIGN, 2020);
	1.2 (Analyze) Based on an initial given repertoire, the student should be able to locate and relate biodesign projects to existing biodesign frameworks;	Presentation of the main frameworks that organize biodesign;	
	1.3 (Evaluate) The student should get to know the main ethical reflections in biodesign and exercise empathy with other living beings;	Presentation of some of the main ethical reflections in biodesign and the exercise "Small acts of being";	
	1.4 (Create) Articulating the initial repertoire presented in class, the student should be able to formulate their own initial ideas for a biodesign project to be developed in the course (with mycelium composite);	Presentation of a repertoire of diverse biodesign initiatives, based on the phylogenetic organization. Examples with corals, silkworms, bees, plants, fungi, and bacteria;	
	1.5 (Apply) Using database tools such as Google Scholar, Web of Science, and others, students should be able to select relevant scientific material for the project they will develop, summarizing important information;	Extra-class activity of finding, reading, schematizing, and taking notes on a scientific design paper involving mycelium;	
2	2.1/3.1 /5.2 (Apply / create) Students should be able to take into consideration the particularities of design in collaboration with living organisms in their own design	Presentation of design practices in biodesign such as tinkering, Technology Readiness Level, Material Driven Design (MDD), design for complexity approaches;	In the second class, students are introduced to biodesign methodological practices as presented in the literature – important practices such as the Material Driven Design Method, design for complexity approaches, and Dade-

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Table 13 –Learning objectives, activities and application script

Lesson	Learning objective	Activity	Application script
	practices, in the project being developed in the course;		Robertson's explanation for the Technology Readiness Level are presented (2021). Characteristics of designing with other living organisms, like the thinking about the time dimension, are explained and the most common ways of beginning a project in collaboration with other living organisms are presented. Furthermore, students are given an introduction about the organism they will collaborate with: *Ganoderma lucidum.* This introduction is given by a Bioprocess Engineering And Biotechnology student. At this point students are introduced to the task of developing a project throughout the course, they will use mycelium. The teams are organized to sit together and a series of practical exercises are conducted, beginning with the MA2E4 toolkit (CAMERE; KARANA, 2018b). Students are given a sample of the NeoMatter mycelium material and are asked to describe how they perceive the material on a sensorial, interpretative (meanings), affective (emotions), and performative (actions) dimensions – according to the toolkit guidelines. Later on, a collective brainwriting exercise is conducted to help students to create ideas about possible design applications, a material vision, design themes, and tinkering ideas. The tinkering exercise is explained. For the extra-class work package: a grow-it-yourself kit is given to them so they can plan their first extra-class tinkering experiments. Each group is asked to perform at least 3 tinkering experiments and monitor them in the project journal. Students are also asked to complete the project journal which contains the specific activities: work breakdown structure, project planning, writing brainwriting conclusions, defining the material vision;
	2.2 (Evaluate) Based on the MA2E4 method applied in the classroom, students should be able to evaluate and characterize materials in a sensorial, performative, affective, and interpretative dimension – aiming the creation of a vision for the project they are developing in the course, with the facilitation of a vocabulary;	MA2E4 method in the classroom;	
	2.3 (Understand) Students should get to know the organism they are working with in order to develop empathy and stimulate the assimilation of operational vocabulary of the biological sciences;	In-class presentation on *Ganoderma Lucidum* and extra-class tinkering experiments. In the project journal: MBI catalog card, empathy exercise;	
	2.4 (Create) Participating in the proposed dynamics, students should be able to generate ideas of possibilities of applications by segmentation, ideas of themes, ideas of processes for their projects;	In-class brainwriting;	
	2.5 (Evaluate) Practicing the tools proposed in class, students should be able to develop autonomy to make decisions about an application of the material and a product vision for their projects;	In the project journal: conclusion and summarizing exercises;	
	2.6 (Apply / create) Based on the ideas generated in the class brainwriting, on the repertoire presented in class and from the	Presentation of basic steps for material tinkering, supply of raw materials for extra-class tinkering	

Table continues next page

Table 13 –Learning objectives, activities and application script

Lesson	Learning objective	Activity	Application script
	previous readings, the students should feel able to develop out-of-class experiments (tinkering) and record them in the project journal in a structured manner;	activity. In the project journal: structure for monitoring tinkering activities;	
	2.7 (Analyze / evaluate) Developing their sensibilities in working with other living organisms, students should be able to identify variables that impact the final outcome of their projects by tracking their development, such as the environmental conditions;	In the project journal: structure for monitoring tinkering activities;	
	2.1/3.1 /5.2 (Apply / create) Students should be able to take into consideration the particularities of design in collaboration with living organisms in their own design practices, in the project being developed in the course;	In-depth case study Mush and Furf Design - presentation of work dynamics, use of tools and project stages, strategic positioning approaches;	
3	3.2 (Evaluate) Practicing the tools proposed in class, students should be able to develop autonomy to make decisions on strategic positioning and price positioning for their projects;	Presentation of project tools, such as the empathy map (CANVAS), the product positioning map, and price positioning, product expression panels (moodboards). In-class guidance to assist project scoping. Extra-class exercises in the project journal;	The third lesson begins with the in-depth case study of Mush and Furf, presenting the design process model previously developed. Instructions are then given for extra-class activities: product positioning graph in relation to competitors, product price positioning, Empathy Map Canvas (GRAY, 2017), and guidelines for moodboards and product expression. Finally, each group has the possibility to talk to the professor/instructor for guidance. Extra-class activities also were concept sketching and development, including sketches in the project journal;
	3.3 (Create) Based on the previous information and exercises, students should be able to develop design alternatives for their projects;	Extra-class sketching and brainstorming for product solutions;	
4	4.1 (Understand) Students will understand the process of developing the mycelium	Presentation of the development process of the raw material for mycelium composites	The fourth module begins with a presentation of the development of the mycelium raw material with the

Table continues next page

Table 13 –Learning objectives, activities and application script

Lesson	Learning objective	Activity	Application script
	composite raw material in a domestic (non-laboratory) context so that if desired, they can produce it independently;	considering a domestic (non-laboratory) environment: a visual map;	company NeoMatter. Schematics are provided to the students, on how they could develop the raw materials at home. Each group makes a presentation of partial results and receives written feedback from four reviewers: this researcher, the course's official professor, NeoMatter's CEO, and a Bioprocess Engineering and Biotechnology student. The feedback is given upon the tinkering experiments and the concept, and improvement suggestions are also given; Extra-class activities comprised the project's further development, prototyping with the mycelium, and monitoring in the project journal;
	4.2 (Create) Consolidate a concise communication of the ongoing project, in order to move toward its realization;	In-class space for communication of partial results;	
	4.3/6.1 (Understand) Students should be able to identify possibilities for improvement in the project based on received feedback;	Written feedbacks;	
5	5.1 (Understand) Students should get to know the dynamics of one of the main digital representation tools used in the practice of design with living organisms;	Introductory presentation of a design representation tool for design with the living – Grasshopper;	The fifth lesson begins with a small introduction to Grasshopper. Next, a presentation of the in-depth case study of Fullgrown is made with the previously developed design process model. Finally, each group has the possibility to talk to the professor/instructor for guidance. Extra-class activities at the project journal involved the reframing of the project's timeline, the pricing of the project and of the final product, thinking about selling strategies and developing a product flyer to promote and release the product, and writing project conclusions;
	2.1/ 3.1 /5.2 (Apply / create) Students should be able to take into consideration the particularities of design in collaboration with living organisms in their own design practices, in the project being developed in the course;	Detailed Fullgrown case study with emphasis on project representation strategies and strategic aspects;	
	5.3 (Apply/ analyze) Reflect on the pricing of the product, reassessing the initial strategy established for the project and readjusting it if necessary;	In the project diary: introduction to product price thinking, reevaluation of product positioning strategy;	
	5.4 (Apply/analyze) Reflect on the project management, comparing the planned to the executed;	Extra-class exercise in the project journal: a re-evaluation of the project timeline. Management: what was planned and what really happened?	
	5.5 (Create) Students should be able to develop a communication piece for the product's promotion.	Extra-class exercise producing product marketing material;	

Table continues next page

Table 13 –Learning objectives, activities and application script

Lesson	Learning objective	Activity	Application script
6	4.3/6.1 (Understand) Students should be able to identify possibilities for improvement in the project based on received feedback;	Final presentation with written feedback.	The time of the final lesson is reserved for the group's final presentations. Written feedback is given by four reviewers: this researcher, the course's official professor, NeoMatter's CEO, and a Bioprocess Engineering And Biotechnology student. Feedback is given over an evaluation rubric which considers the project's feasibility and process comprehension, concept quality, form-giving, product market placement, time management, and presentation quality.

Source: Elaborated by the author (2023)

The next section introduces the framework's evaluation rubric.

4.4.5 Framework evaluation rubric

For students to evaluate their experience with the framework, an evaluation rubric was designed. Table 14 shows an example of an item of the evaluation rubric, which is organized according to the modules/lessons. Each learning objective and activity is presented side-by-side for students to rate according to their perception: **NA – The learning objective was not met; AP - The learning objective was partially met; A – The learning objective was met; or NP- I could not participate, I cannot evaluate.**

Table 14 –Example of an item of the evaluation rubric

Activity	**Learning objectives**	**NA**	**AP**	**A**	**NP**
Presentation of the main concepts of the field - what is biodesign, its place in relation to biomimetics, tinkering, growing design and others;	1.1 (Understand) The students should be able to clearly associate biodesign concepts and recognize them in the future;				

Source: Elaborated by the author (2022)

After every module/lesson, two open questions are presented for students to reply: (1) When did I think I learned the most in this module? (2) What could have been better in this module?

In the next sections, the application of the framework and its evaluation are described.

4.5 EXPERIENCES IN BIODESIGN TEACHING AND LEARNING

The evaluation took place at the mandatory course "OD508- Materials and Processes III", from July 21, 2022, to August 25, 2022. This course happens in the third year of the product design undergraduate progra. There were six presential lessons of 3 hours with additional activities for students to do at home. 37 students joined in the activity, working in 8 groups of 4 people, one group of 3, and one group of 2. The application script was rigorously followed and a physical copy of the project journal was handed over for students to use, along with the original digital file. Each group developed a product design project with mycelium. All slides were made available for students after the classes. Professor Dr. Caroline Müller, responsible for the course, accompanied the framework's evaluation, as well as Caroline Aimi Fukuda, a student in the final year of the Bioprocess Engineering and Biotechnology course. Luiz Eduardo Piá de Andrade, CEO of the NeoMatter mycelium startup, participated in the evaluation and feedback of the projects. Students' projects were evaluated according to a rubric and overt observation was registered following each learning objective. Additionally, the course professor also evaluated the framework through the evaluation rubric. In the sixth and last class, students were invited to evaluate the framework according to the evaluation rubric. The overt observation, the student's framework evaluation results, and the evaluation by the course professor were later triangulated. Later on, the framework's contingency heuristics were formulated, and final insights from the immersion at the cluster Matters of Activity about the framework were included.

In the next sections, the students' projects' results and their evaluation are presented, following the overt observation results, the framework's evaluation by the students, the evaluation by the course professor – then the triangulation of the results. Finally, the contingency heuristics for the framework are detailed and the immersion insights from Matters of Activity are presented.

4.5.1 Project results and evaluation

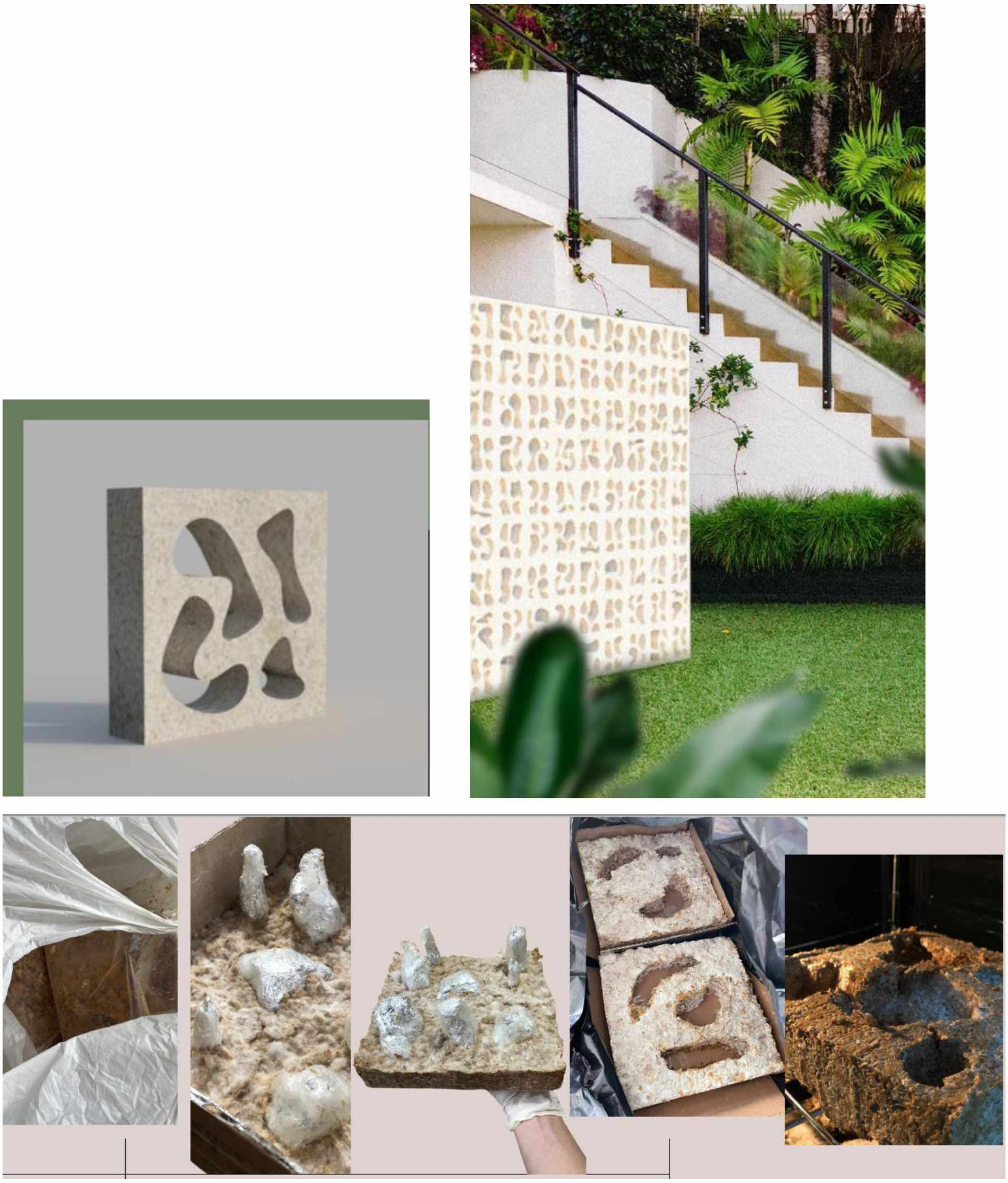
The projects were developed throughout the six weeks, some project activities were conducted in class, like collective brainwritings, and some happened in the student's homes, like tinkering. In Appendix 6, the project results for each team and their evaluation are presented. Here, one example is given, the development of a cobogó – but others include the development of jewelry, a toy, lamps, and even a chair. The evaluation considered the project's feasibility and process comprehension, concept quality, form-giving, product market placement, time management, and presentation quality. One group did not present. Not all teams could develop prototypes, and those that could, only gost to make it once. It would be recommended that the projects would be further developed. The students` names are substituted by codes to preserve their identities.

Cobogó Bió – Students A7, A8, A29 and A31

Cobogó Bió is a hollow construction element, traditional in Brazilian architecture, used to divide rooms allowing air and light to come through. The students' vision for the product was: "[to] Use biomimetic design as a design premise. Biomimetic design understands form as a result of the elements of nature. In this way, a structure must be developed based on this inspiration; a pattern that generates a product capable of symbolizing this process" (by the students, 2022, our translation).

The perceptual positioning for the market was defined as "classic" and "contemporary", priced at 50 dolars, to be sold in sets of 10 pieces. A highlight of the project was the competitor research and time management. Figure 44 presents the project's renderings and prototyping.

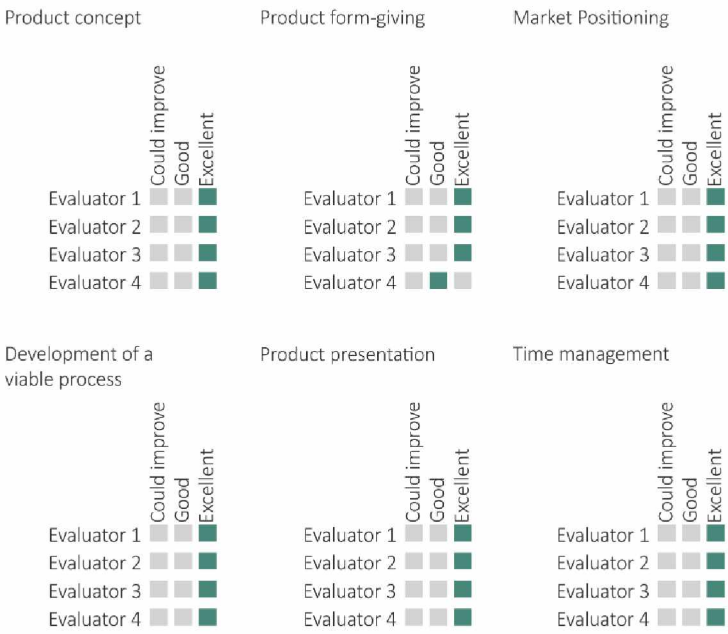
Figure 44 – Cobogó Bió rendering and prototype production



Source: elaborated by the students (2022)

Figure 62 shows the ratings for the project, which was mainly evaluated as "excellent".

Figure 45 – Evaluation of the Cobogó Bió project



Source: Elaborated by the author (2022)

4.5.2 Overt observation

Overt observation took place throughout the six weeks. Table 15 presents the overt observation notes according to each learning objective.

Table 15 –Overt observation notes

Learning Objective (Condition Actor Behavior Degree)	**Observations**
1.1 (Understand) The students should be able to clearly associate biodesign concepts and recognize them in the future;	It looks like there was too much content at the same time and concepts could be better distributed across the lessons instead of being concentrated in the first lesson;
1.2 (Analyze) Based on an initial given repertoire, the student should be able to locate and relate biodesign projects to existing biodesign frameworks;	Time was too short for exercising the different frameworks with the students, it looks like they will not be able to remember them. However, it seems that it helped them to see the different possible categories of biodesign;

Table continues next page

Table 15 –Overt observation notes

Learning Objective (Condition Actor Behavior Degree)	**Observations**
1.3 (Evaluate) The student should get to know the main ethical reflections in biodesign and exercise empathy with other living beings;	Students engaged in the empathy exercise and in conversations about ethics in the classroom - so it seems the purpose was fulfilled;
1.4 (Create) Articulating the initial repertoire presented in class, the student should be able to formulate their own initial ideas for a biodesign project to be developed in the course (with mycelium composite);	The repertoire seemed to interest the students in class and they successfully engaged in the creative activities developed in the sequence;
1.5 (Apply) Using database tools such as Google Scholar, Web of Science, and others, students should be able to select relevant scientific material for the project they will develop, summarizing important information;	Students successfully found and developed schematizations of scientific papers about mycelium;
2.1/3.1 /5.2 (Apply / create) Students should be able to take into consideration the particularities of design in collaboration with living organisms in their own design practices, in the project being developed in the course;	Reading the students' conclusions and observing their comments on the classroom, it seems that some of the particularities were highly perceived by them, like the unpredictability of results – but it seems students were led to focus too much on the product strategy and the deadlines, making them pay more attention to the urgency and not developing new designerly sensibilities enough;
2.2 (Evaluate) Based on the MA2E4 method applied in the classroom, students should be able to evaluate and characterize materials in a sensorial, performative, affective, and interpretative dimension – aiming the creation of a vision for the project they are developing in the course, with the facilitation of a vocabulary;	Many students came after class with questions about the material vision, so it seems this concept was not presented clearly enough. On the other hand, it seems that conducting the MA2E4 in the classroom enriched the students` brainwriting later;
2.3 (Understand) Students should get to know the organism they are working with in order to develop empathy and stimulate the assimilation of operational vocabulary of the biological sciences;	It is difficult to assess how much students could learn and understand about the explanations given about *Ganoderma lucidum;*
2.4 (Create) Participating in the proposed dynamics, students should be able to generate ideas of possibilities of applications by segmentation, ideas of themes, ideas of processes for their projects;	Students successfully created many ideas;
2.5 (Evaluate) Practicing the tools proposed in class, students should be able to develop autonomy to make decisions about an application of the material and a product vision for their projects;	Students successfully made decisions about a product to be developed;
2.6 (Apply / create) Based on the ideas generated in the class brainwriting, on the repertoire presented in class and from the previous readings, the students should feel able to develop out-of-class experiments (tinkering) and record them in the project journal in a structured manner;	Most groups of students took more time than expected with their tinkering activities. It seems they could not decide on what experiments to do and who would perform them. Some students let the grow-it-yourself kit spoil and did not do the tinkering experiments. However, some students developed very creative and varied experiments;
2.7 (Analyze / evaluate) Developing their sensibilities in working with other living organisms, students should be able to identify variables that impact the	As most tinkering experiments did not happen in the expected timeframe, it seems there was not time enough for students to take their own conclusions on what variables could impact their experiments;

Table 15 –Overt observation notes

Learning Objective (Condition Actor Behavior Degree)	Observations
final outcome of their projects by tracking their development, such as the environmental conditions;	
3.2 (Evaluate) Practicing the tools proposed in class, students should be able to develop autonomy to make decisions on strategic positioning and price positioning for their projects;	Students successfully proposed a pricing and market positioning strategy for their products;
3.3 (Create) Based on the previous information and exercises, students should be able to develop design alternatives for their projects;	Students successfully developed designs for their intended products;
4.1 (Understand) Students will understand the process of developing the mycelium composite raw material in a domestic (non-laboratory) context so that if desired, they can produce it independently;	It is difficult to assess if they could indeed understand how the raw material for the grow-it-yourself kit can be made at home;
4.2/6.1 (Create) Consolidate a concise communication of the ongoing project, in order to move toward its realization;	Not all students presented their complete partial results – indicating that instructions could be clearer about what was to be presented. In the final presentation all items requested were successfully presented by students;
4.3/6.2 (Understand) Students should be able to identify possibilities for improvement in the project based on received feedback;	Projects improved upon feedback;
5.1 (Understand) Students should get to know the dynamics of one of the main digital representation tools used in the practice of design with living organisms;	Despite the discussion that the presentation of Grasshopper enabled in class, it does not seem that students could grasp the possibilities of its application in biodesign;
5.3 (Apply/ analyze) Reflect on the pricing of the product, reassessing the initial strategy established for the project and readjusting it if necessary;	Students successfully priced their products considering the human and material resources used and the product's intended strategic position;
5.4 (Apply/analyze) Reflect on the project management, comparing the planned to the executed;	Students successfully compared their time schedules, making comments on what changed in the end compared to what was planned;
5.5 (Create) Students should be able to develop a communication piece for the product's promotion.	Students successfully presented a marketing promotion piece of their products.

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Source: Elaborated by the author (2023)

The next section describes the framework evaluation by the students.

4.5.3 Framework evaluation by students

The evaluation was organized on the last day of the presential classes and took about 1 hour. It followed the structure presented in section 4.4.5. Thirty-one students were present at the moment and participated in this step. Table 16 shows the students' ratings for each learning objective. The ratings are presented through a frequency distribution graph, showing the number of ratings and what they mean in percentage considering the total (N=31). The rating options were the following: NA – The learning objective was not met; AP - The learning objective was partially met; A – The learning objective was met; or NP- I could not participate, I cannot evaluate.

Table 16 – Learning objectives and the evaluation by the students

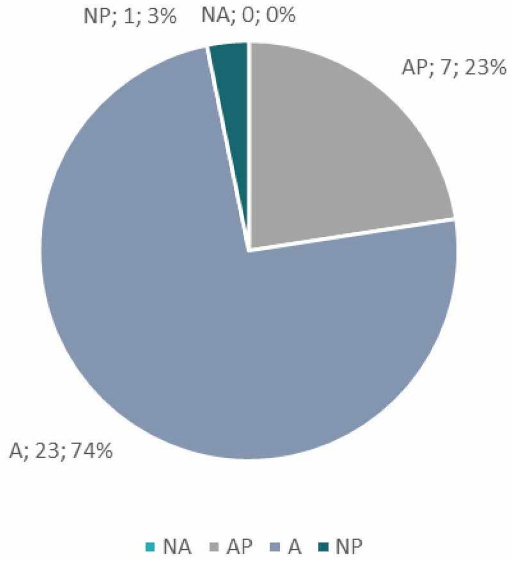
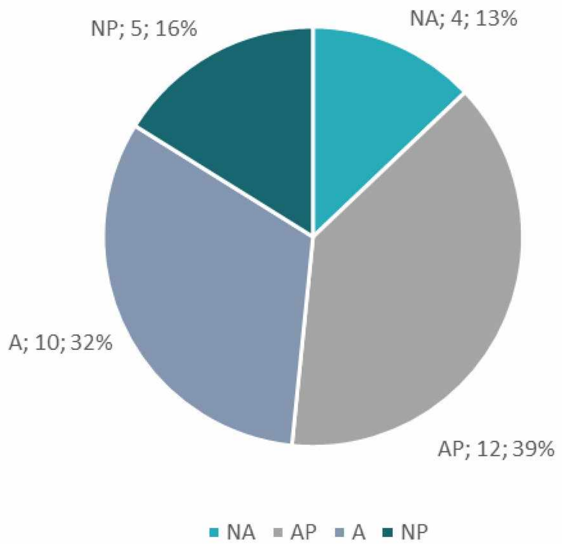
Learning Objective	Evaluation
1.1 (Understand) The students should be able to clearly associate biodesign concepts and recognize them in the future; NA – The learning objective was not met; AP - The learning objective was partially met; A – The learning objective was met; NP- I could not participate, I cannot evaluate	
1.2 (Analyze) Based on an initial given repertoire, the student should be able to locate and relate biodesign projects to existing biodesign frameworks;	

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Table 16 – Learning objectives and the evaluation by the students

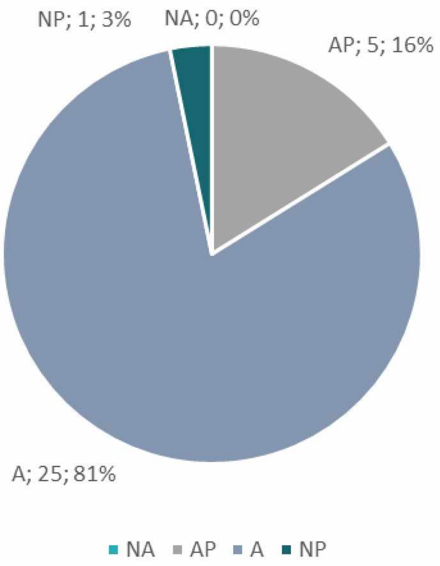
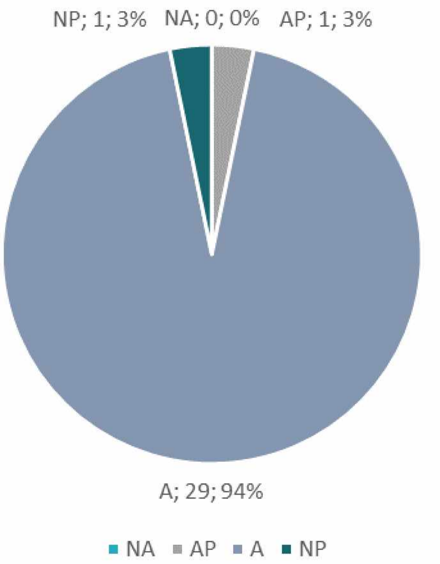
Learning Objective	**Evaluation**
1.3 (Evaluate) The student should get to know the main ethical reflections in biodesign and exercise empathy with other living beings; NA – The learning objective was not met; AP - The learning objective was partially met; A – The learning objective was met; NP- I could not participate, I cannot evaluate	
1.4 (Create) Articulating the initial repertoire presented in class, the student should be able to formulate their own initial ideas for a biodesign project to be developed in the course (with mycelium composite);	

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Table 16 – Learning objectives and the evaluation by the students

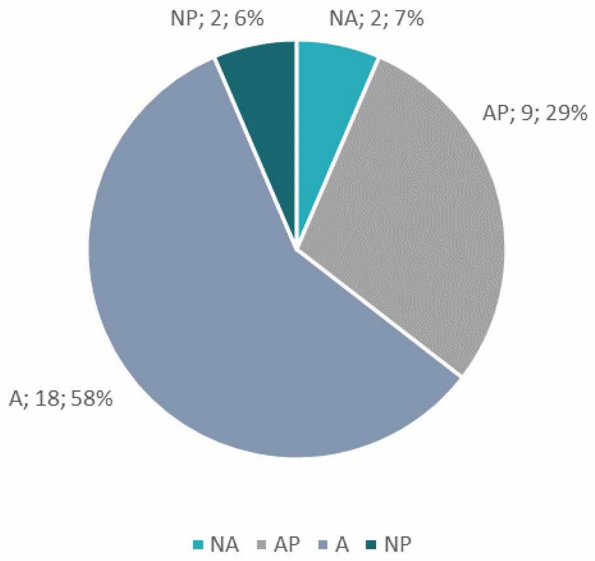
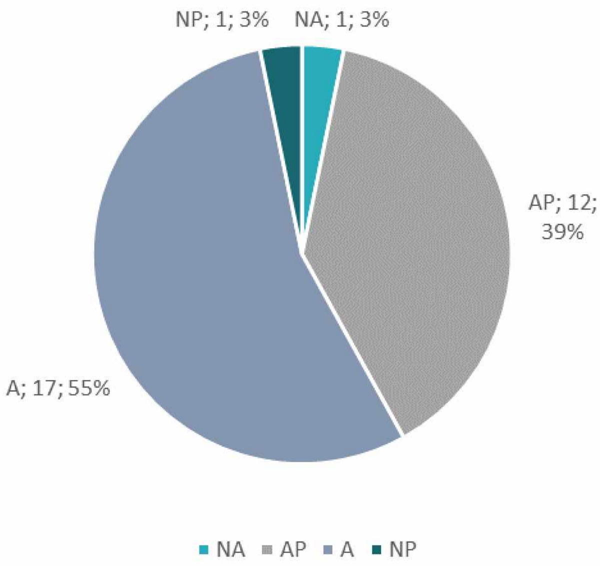
Learning Objective	Evaluation
1.5 (Apply) Using database tools such as Google Scholar, Web of Science, and others, students should be able to select relevant scientific material for the project they will develop, summarizing important information; NA – The learning objective was not met; AP - The learning objective was partially met; A – The learning objective was met; NP- I could not participate, I cannot evaluate	
2.1/3.1 /5.2 (Apply / create) Students should be able to take into consideration the particularities of design in collaboration with living organisms in their own design practices, in the project being developed in the course;	

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Table 16 – Learning objectives and the evaluation by the students

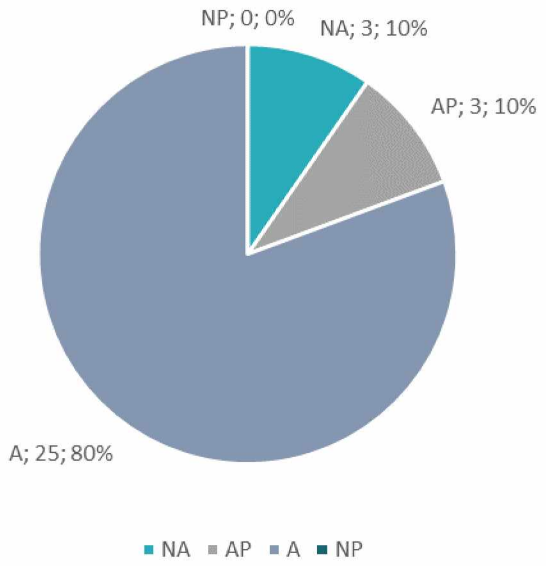
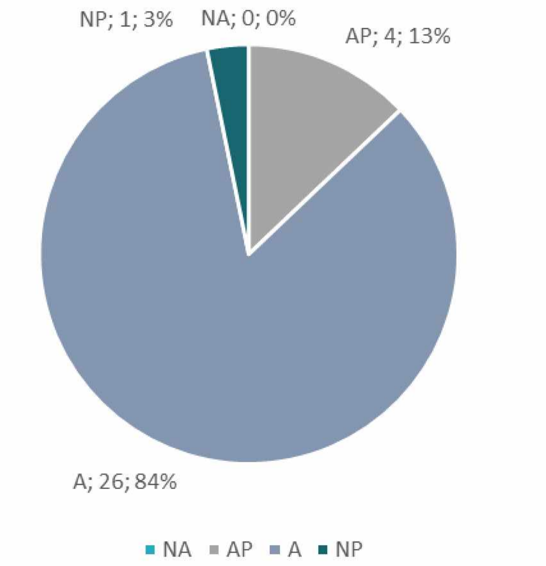
Learning Objective	Evaluation
	
	

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Table 16 – Learning objectives and the evaluation by the students

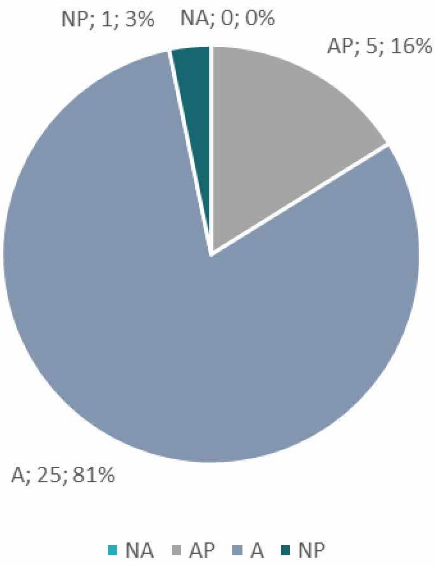
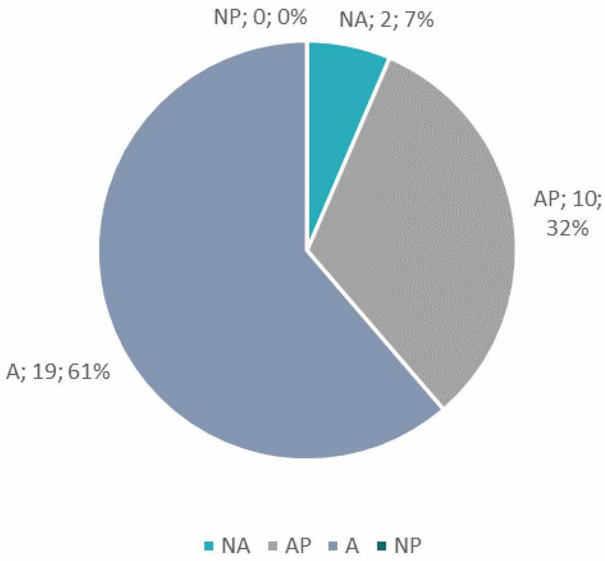
Learning Objective	Evaluation
2.2 (Evaluate) Based on the MA2E4 method applied in the classroom, students should be able to evaluate and characterize materials in a sensorial, performative, affective, and interpretative dimension – aiming the creation of a vision for the project they are developing in the course, with the facilitation of a vocabulary; NA – The learning objective was not met; AP - The learning objective was partially met; A – The learning objective was met; NP- I could not participate, I cannot evaluate	
2.3 (Understand) Students should get to know the organism they are working with in order to develop empathy and stimulate the assimilation of operational vocabulary of the biological sciences;	

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Table 16 – Learning objectives and the evaluation by the students

<table>
<tr><th>Learning Objective</th><th>Evaluation</th></tr>
<tr><td>2.4 (Create) Participating in the proposed dynamics, students should be able to generate ideas of possibilities of applications by segmentation, ideas of themes, ideas of processes for their projects;

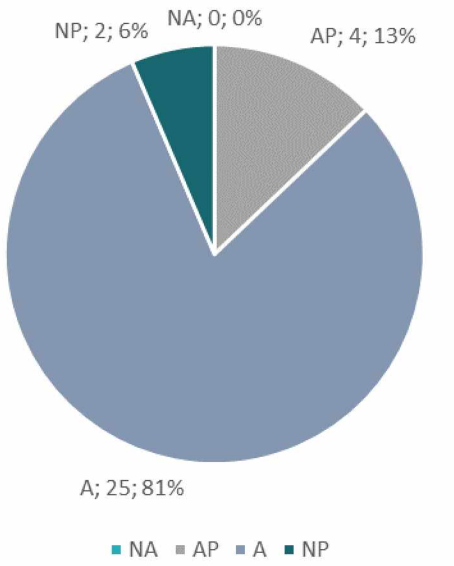
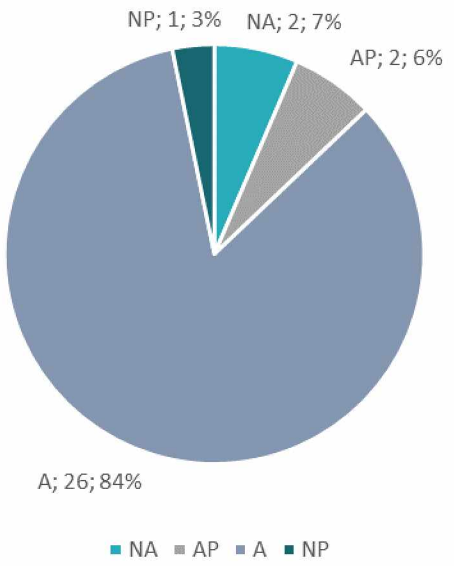
NA – The learning objective was not met;
AP - The learning objective was partially met;
A – The learning objective was met;
NP- I could not participate, I cannot evaluate</td><td>
</td></tr>
<tr><td>2.5 (Evaluate) Practicing the tools proposed in class, students should be able to develop autonomy to make decisions about an application of the material and a product vision for their projects;</td><td>
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Table 16 – Learning objectives and the evaluation by the students

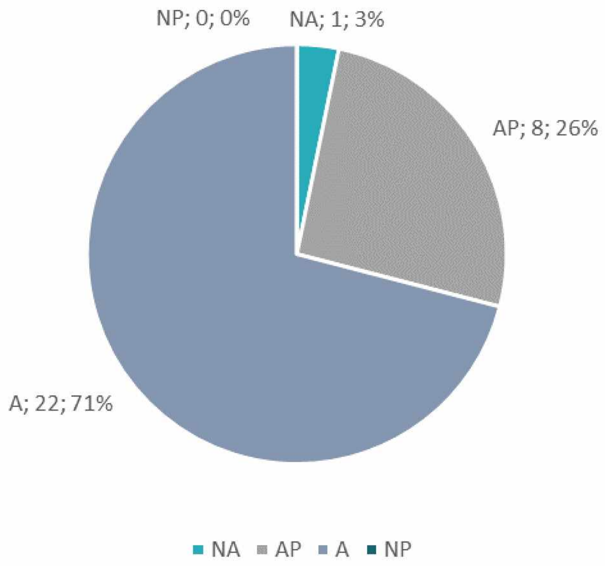
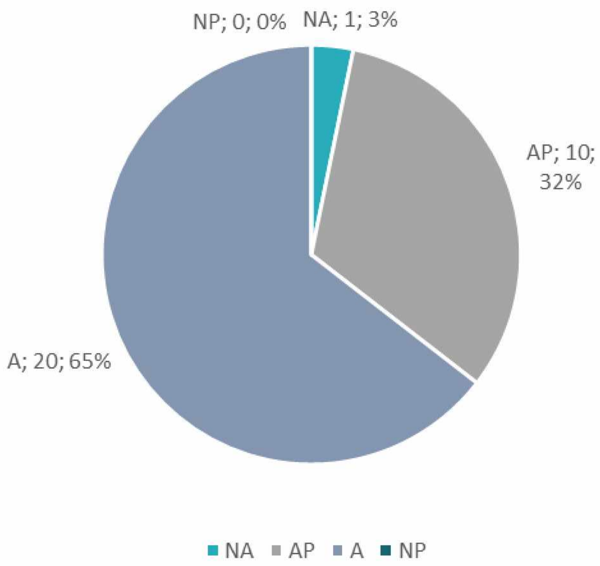
Learning Objective	Evaluation
2.6 (Apply / create) Based on the ideas generated in the class brainwriting, on the repertoire presented in class and from the previous readings, the students should feel able to develop out-of-class experiments (tinkering) and record them in the project journal in a structured manner; NA – The learning objective was not met; AP - The learning objective was partially met; A – The learning objective was met; NP- I could not participate, I cannot evaluate	
2.7 (Analyze / evaluate) Developing their sensibilities in working with other living organisms, students should be able to identify variables that impact the final outcome of their projects by tracking their development, such as the environmental conditions;	

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Table 16 – Learning objectives and the evaluation by the students

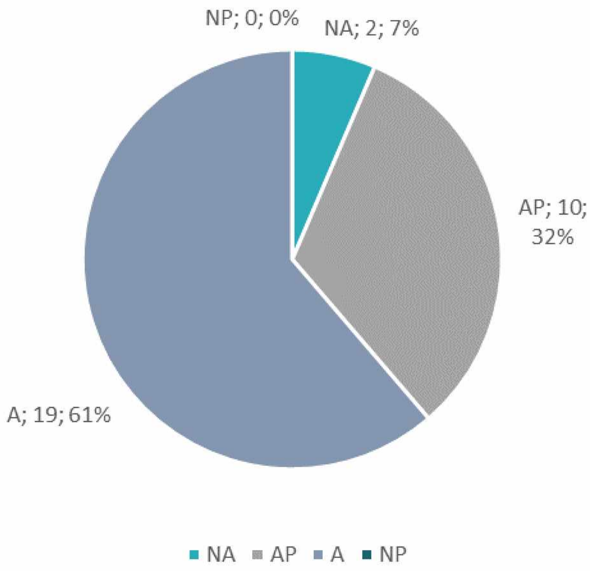
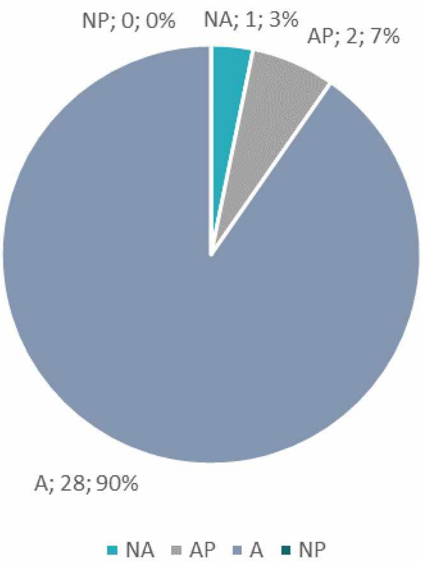
Learning Objective	Evaluation
3.2 (Evaluate) Practicing the tools proposed in class, students should be able to develop autonomy to make decisions on strategic positioning and price positioning for their projects; NA – The learning objective was not met; AP - The learning objective was partially met; A – The learning objective was met; NP- I could not participate, I cannot evaluate	
3.3 (Create) Based on the previous information and exercises, students should be able to develop design alternatives for their projects;	

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Table 16 – Learning objectives and the evaluation by the students

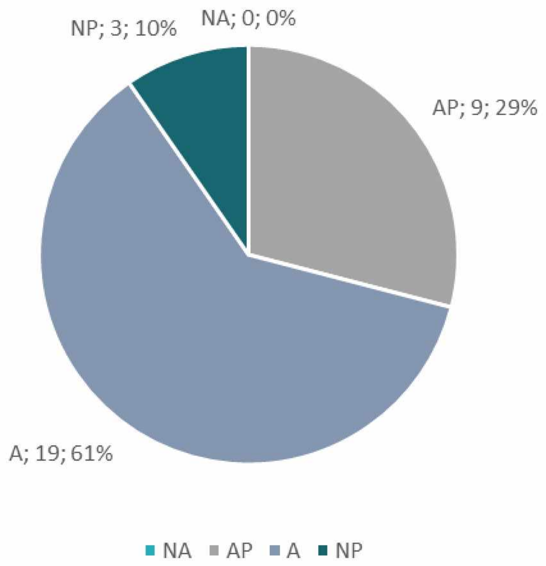
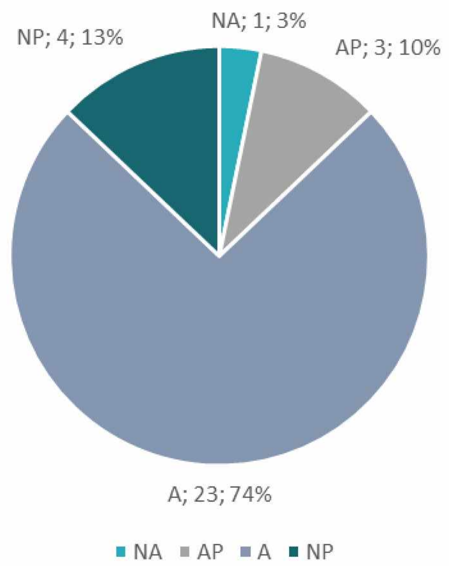
Learning Objective	Evaluation
4.1 (Understand) Students will understand the process of developing the mycelium composite raw material in a domestic (non-laboratory) context so that if desired, they can produce it independently; NA – The learning objective was not met; AP - The learning objective was partially met; A – The learning objective was met; NP- I could not participate, I cannot evaluate	
4.2/6.1 (Create) Consolidate a concise communication of the ongoing project, in order to move toward its realization;	

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Table 16 – Learning objectives and the evaluation by the students

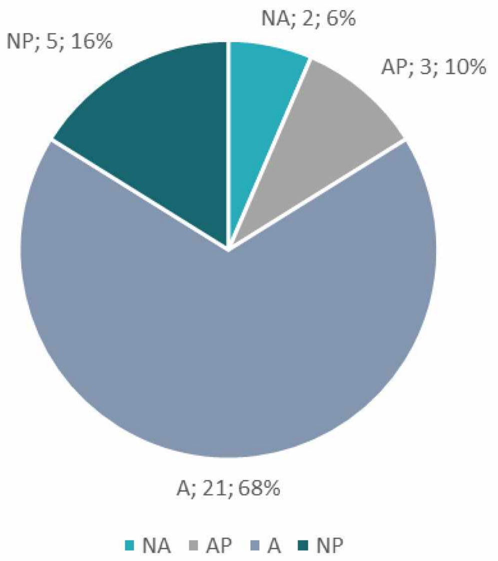
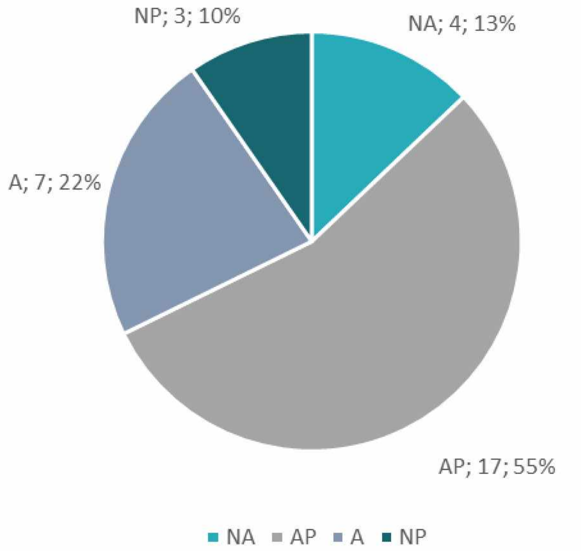
Learning Objective	Evaluation
4.3/6.2 (Understand) Students should be able to identify possibilities for improvement in the project based on received feedback; NA – The learning objective was not met; AP - The learning objective was partially met; A – The learning objective was met; NP- I could not participate, I cannot evaluate	
5.1 (Understand) Students should get to know the dynamics of one of the main digital representation tools used in the practice of design with living organisms;	

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Table 16 – Learning objectives and the evaluation by the students

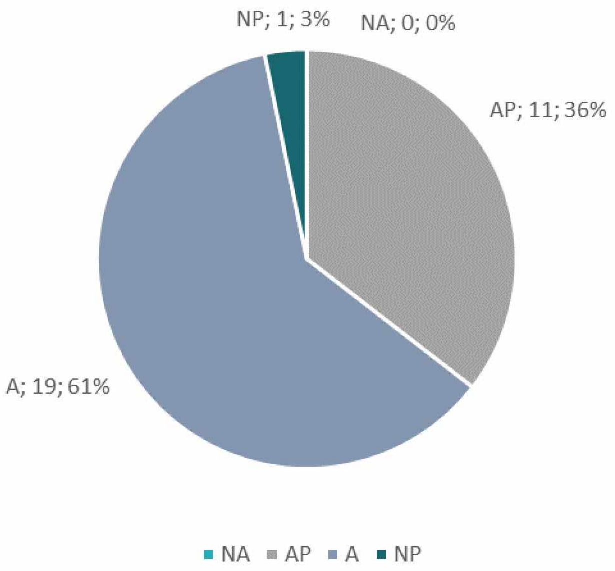
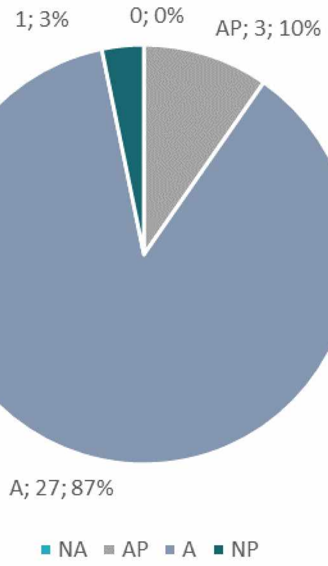
Learning Objective	Evaluation
5.3 (Apply/ analyze) Reflect on the pricing of the product, reassessing the initial strategy established for the project and readjusting it if necessary; NA – The learning objective was not met; AP - The learning objective was partially met; A – The learning objective was met; NP- I could not participate, I cannot evaluate	
5.4 (Apply/analyze) Reflect on the project management, comparing the planned to the executed;	

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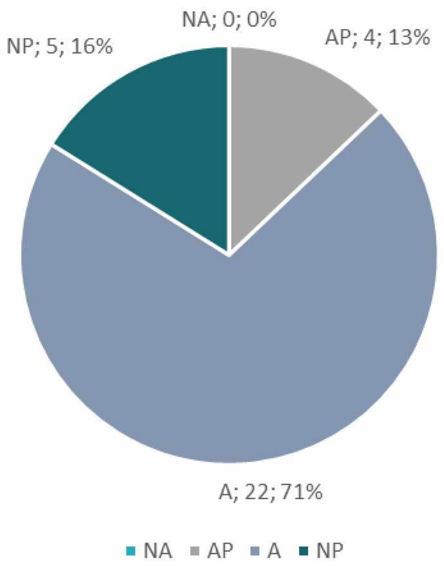
Table 16 – Learning objectives and the evaluation by the students

Learning Objective	Evaluation
5.5 (Create) Students should be able to develop a communication piece for the product's promotion. NA – The learning objective was not met; AP - The learning objective was partially met; A – The learning objective was met; NP- I could not participate, I cannot evaluate	

Source: Elaborated by the author (2023)

According to the students` perception of their own learning, it seems that most of the learning objectives were rated more than 50% in the category: "A – The learning objective was met". Exceptions are the learning objectives "5.1 (Understand) Students should get to know the dynamics of one of the main digital representation tools used in the practice of design with living organisms", which received 55% of the ratings as "AP - The learning objective was partially met"; and "1.2 (Analyze) Based on a given repertoire, the student should be able to locate and relate biodesign projects to existing biodesign frameworks", which received 39% "AP", 13% "NA – The learning object was not met", and 16% "NP- I could not participate, I cannot evaluate".

Regarding learning objective "2.1/3.1 /5.2 (Apply / create) Students should be able to take into consideration the particularities of design in collaboration with living organisms in their own design practices, in the project being developed in the course", the question was repeated three times in the context of each module. On the first time, 55% of the students answered "A' and 39% answered "AP"; while on the second time, it seems that an improvement was made: 80% replied "A" and 10% replied "AP"; finally, another improvement seems to have happened in the third time: 84% answered "A" and 13% answered "AP".

Good ratings were also given with respect to the learning outcomes of the learning objectives 1.4; 2.2; 2.4; 2.5; 3.3; 5.2; and 5.4:

- "1.4 (Create) Articulating the initial repertoire presented in class, the student should be able to formulate their own initial ideas for a biodesign project to be developed in the course (with mycelium composite)" – 94% "A" ratings;
- "2.2 (Evaluate) Based on the MA2E4 method applied in the classroom, students should be able to evaluate and characterize materials in a sensorial, performative, affective, and interpretative dimension – aiming the creation of a vision for the project they are developing in the course, with the facilitation of a vocabulary" - 81% "A" ratings;
- "2.4 (Create) Participating in the proposed dynamics, students should be able to generate ideas of possibilities of applications by segmentation, ideas of themes, ideas of processes for their projects" – 81% "A" ratings;
- "2.5 (Evaluate) Practicing the tools proposed in class, students should be able to develop autonomy to make decisions about an application of the material and a product vision for their projects" – 84% "A" ratings;
- "3.3 (Create) Based on the previous information and exercises, students should be able to develop design alternatives for their projects" – 90% "A" ratings;
- "5.2 (Apply / create) Students should be able to take into consideration the particularities of design in collaboration with living organisms in their own design practices, in the project being developed in the course" – 84% "A" ratings;
- "5.4 (Apply/analyze) Reflect on the project management, comparing the planned to the executed" – 87% "A" ratings.

Not all students replied to the open-written questions. When two or more comments from different students converged, they are reported below:

For the first module, when asked (1) When did I think I learned the most in this module? - 6 students wrote that they thought they learned the most through reading and schematizing the scientific paper; 3 students replied they had learned the most with the "Small acts of being" activity; and 13 thought they learned the most through the biodesign representation repertoire. For the question (2) What could have been better in this module?

– 3 students reported difficulties finding scientific papers (one specifically reported the lack of papers in Portuguese); 4 answered they could profit from having more time in this module; and 2 wished they had more time or deepening in the “Small acts of being” activity.

In Module 2 to the question (1) When did I think I learned the most in this module? – 12 students replied they think they learned the most manipulating the material samples and tinkering with the material; 4 answered they learned the most when characteristics of biodesign process were presented; 6 replied the MA2E4 activity helped them learn the most; 6 answered the in-class creativity tools, like the brainwriting, helped them the most; and 3 thought it was the project journal which helped the most. To the question (2) What could have been better in this module? - 7 students replied they feel more time could have helped; 4 wished they had more instructions for tinkering and working with the mycelium; 3 wished the tinkering activity was more related to the final product (more prototyping time); 3 felt that they could have had more instructions about the project journal; and 2 found some technical terms were confusing.

In the third module, to the question (1) When did I think I learned the most in this module? – 10 students replied it was on the case studies; 4 students answered it was with the empathy map; and 11 students replied they think they learned the most with the perception positioning map and price positioning map exercises. To the question (2) What could have been better in this module? - 7 replied they wish they had more time in this module; 7 found difficulties with the empathy map; and 4 had difficulties with the perception positioning map and price positioning map.

For module 4, to the question (1) When did I think I learned the most in this module? – 7 students replied they learned the most through the partial results presentations, when seeing what the other colleagues had done and shared their own results; 11 wrote they learned the most through the written feedback; and 6 replied they learned the most when “how the material could be produced at home was presented”. To the question (2) What could have been better in this module? – 4 wrote they wished they had more time; and 2 replied they wished there was a space at the university for the practical activities.

Finally, for module 5, to the question (1) When did I think I learned the most in this module? – 6 wrote they learned the most at the case studies; 9 thought they learned the most at the activities of schedule and product strategy reevaluation (project management); 2 said they learned the most developing the product release and promotion information (flyer); and

8 wrote they learned the most at the product pricing activities. To the question (2) What could have been better in this module? – 10 wrote they wish they had more time at this module; 4 found they needed more help in the product pricing activity; 3 thought they could not learn much at the software presentation for representation with living materials; and 2 think they needed more help in the product release information (flyer) development.

4.5.4 Framework evaluation by the course professor

For the triangulation process, the course professor also evaluated the framework using the evaluation rubric. At the open questions at the end of each module, Prof. Dr. Caroline Müller opted to only make remarks on "What could have been better in this module?" – because the question "When did I think I learned the most in this module?" did not apply. Table 17 presents the evaluation results. The rating options were the following: NA – The learning objective was not met; AP - The learning objective was partially met; A – The learning objective was met; or NP- I could not participate, I cannot evaluate. The comments were originally written in Portuguese and were translated into English.

Table 17 –Evaluation by the course professor

Learning Objective (Condition Actor Behavior Degree)	Evaluation	What could have been better in this module?
1.1 (Understand) The students should be able to clearly associate biodesign concepts and recognize them in the future;	A	"I believe that a strategy that could have been developed was for students to build GRS's [Graphic Representations for Synthesis] of what they were learning in class, as a way to individually develop the process of understanding and assimilating the content."
1.2 (Analyze) Based on an initial given repertoire, the student should be able to locate and relate biodesign projects to existing biodesign frameworks;	A	
1.3 (Evaluate) The student should get to know the main ethical reflections in biodesign and exercise empathy with other living beings;	A	
1.4 (Create) Articulating the initial repertoire presented in class, the student should be able to formulate their own initial ideas for a biodesign project to be developed in the course (with mycelium composite);	A	
1.5 (Apply) Using database tools such as Google Scholar, Web of Science, and others, students should be able to select relevant scientific material for the project they will develop, summarizing important information;	NP	
2.1/3.1 /5.2 (Apply / create) Students should be able to take into consideration the particularities of design in collaboration with living organisms in their own design practices, in the project being developed in the course;	A (2.1)	"In item 2.2 I indicated that it [the learning objective] was partially met because I think it is subjective to evaluate "sensorial, performatively, affective, and interpretative dimensions" - it can bring difficult answers to measure if the learning objective was met. In item 2.7 [later she added, 2.6 too] I also think that as a teacher our relationship with the monitoring done by the students is partial. Some groups were more committed to presenting the steps, contacted the instructor Elisa, others did not commit."
	AP (3.1)	
	AP (5.1)	
2.2 (Evaluate) Based on the MA2E4 method applied in the classroom, students should be able to evaluate and characterize materials in a sensorial, performative, affective, and interpretative dimension – aiming the creation of a vision for the project they are developing in the course, with the facilitation of a vocabulary;	AP	
2.3 (Understand) Students should get to know the organism they are working with in order to develop empathy and stimulate the assimilation of operational vocabulary of the biological sciences;	A	
2.4 (Create) Participating in the proposed dynamics, students should be able to generate ideas of possibilities of applications by segmentation, ideas of themes, ideas of processes for their projects;	A	
2.5 (Evaluate) Practicing the tools proposed in class, students should be able to develop autonomy to make decisions about an application of the material and a product vision for their projects;	A	

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Table 17 –Evaluation by the course professor

Learning Objective (Condition Actor Behavior Degree)	Evaluation	What could have been better in this module?
2.6 (Apply / create) Based on the ideas generated in the class brainwriting, on the repertoire presented in class and from the previous readings, the students should feel able to develop out-of-class experiments (tinkering) and record them in the project journal in a structured manner;	AP	
2.7 (Analyze / evaluate) Developing their sensibilities in working with other living organisms, students should be able to identify variables that impact the final outcome of their projects by tracking their development, such as the environmental conditions;	AP	
3.2 (Evaluate) Practicing the tools proposed in class, students should be able to develop autonomy to make decisions on strategic positioning and price positioning for their projects;	A	"Unfortunately this phase was too quick. I think that if we had more time, we would have discussed and appreciated more calmly the students' generation of concepts, linking it to the methods and examples presented in class."
3.3 (Create) Based on the previous information and exercises, students should be able to develop design alternatives for their projects;	AP	
4.1 (Understand) Students will understand the process of developing the mycelium composite raw material in a domestic (non-laboratory) context so that if desired, they can produce it independently;	AP	"Here I think it would have been very interesting if there had been a video showing the process of developing the material. Most students had difficulty understanding the textures, smells, and the ideal state of the material. I have noticed that working with videos makes the understanding of the production processes in metals easier, for example."
4.2/6.1 (Create) Consolidate a concise communication of the ongoing project, in order to move toward its realization;	A	
4.3/6.2 (Understand) Students should be able to identify possibilities for improvement in the project based on received feedback;	A	
5.1 (Understand) Students should get to know the dynamics of one of the main digital representation tools used in the practice of design with living organisms;	AP	"I think that the Grasshopper tool was presented quickly and for this reason, the students may have had difficulty understanding how it works. I think that item 5.4 was not explored much by the students in their presentations and it is a very important item for projects with living things because it is the one that expands the repertoire about the new materials."
5.3 (Apply/ analyze) Reflect on the pricing of the product, reassessing the initial strategy established for the project and readjusting it if necessary;	A	
5.4 (Apply/analyze) Reflect on the project management, comparing the planned to the executed;	AP	
5.5 (Create) Students should be able to develop a communication piece for the product's promotion.	A	

Source: Elaborated by the author (2023)

In the next section results are triangulated.

4.5.5 Triangulation and pattern matching

The three evaluations' main results - the overt observation, the students' feedback, and the evaluation by the course professor Dr. Caroline Müller – were put together and triangulated. Pattern matching to the learning objectives was performed. Table 18 presents the triangulation process and conclusions. The conclusion was made upon the convergence of the results. Of the 21 learning objectives, 14 were considered met and the other 7 were concluded as partially met.

Table 18 –Triangulation

Learning Objective (Condition Actor Behavior Degree)	Overt Observations	Evaluation by the students	Evaluation by the course professor	Conclusion
1.1 (Understand) The students should be able to clearly associate biodesign concepts and recognize them in the future;	It looks like there was too much content at the same time and concepts could be better distributed across the lessons instead of being concentrated in the first lesson;	NA: 0; 0% AP: 7, 23% A: 23, 74% NP: 1, 3%	A	Although the observation considers the content could be more distributed through the lessons, most students and the course professor marked that this learning objective was met. A
1.2 (Analyze) Based on an initial given repertoire, the student should be able to locate and relate biodesign projects to existing biodesign frameworks;	Time was too short for exercising the different frameworks with the students, it looks like they will not be able to remember them. However, it seems that it helped them to see the different possible categories of biodesign;	NA: 4; 13% AP: 12, 39% A: 10, 32% NP: 5, 16%	A	Although the course professor perceived that the learning objective was met, observations and student evaluations point out that it was partially met. AP
1.3 (Evaluate) The student should get to know the main ethical reflections in biodesign and exercise empathy with other living beings;	Students engaged in the empathy exercise and in conversations about ethics in the classroom - so it seems the purpose was fulfilled;	NA: 0; 0% AP: 5, 16% A: 25, 81% NP: 1, 3%	A	All three evaluations agree that the learning objective was met. A
1.4 (Create) Articulating the initial repertoire presented in class, the student should be able to formulate their own initial ideas for a biodesign project to be developed in the	The repertoire seemed to interest the students in class and they successfully engaged in the creative activities developed in the sequence;	NA: 0; 0% AP: 1, 3% A: 29, 94% NP: 1, 3%	A	All three evaluations agree that the learning objective was met. A

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Table 18 –Triangulation

Learning Objective (Condition Actor Behavior Degree)	Overt Observations	Evaluation by the students	Evaluation by the course professor	Conclusion
course (with mycelium composite);				
1.5 (Apply) Using database tools such as Google Scholar, Web of Science, and others, students should be able to select relevant scientific material for the project they will develop, summarizing important information;	Students successfully found and developed schematizations of scientific papers about mycelium;	NA: 2; 7% AP: 9, 29% A: 18, 58% NP: 2, 6%	NP	The course professor did not participate in this activity. More than half of the students considered that the learning objective was met, the observation also considers it was met. A
2.1/3.1 /5.2 (Apply / create) Students should be able to take into consideration the particularities of design in collaboration with living organisms in their own design practices, in the project being developed in the course;	Reading the students' conclusions and observing their comments on the classroom, it seems that some of the particularities were highly perceived by them, like the unpredictability of results – but it seems students were led to focus too much on the product strategy and the deadlines, making them pay more attention to the urgency and not developing new designerly sensibilities enough;	NA: 1; 3% AP: 12, 39% A: 17, 55% NP: 1, 3%	A (2.1)	According to the student evaluation, this learning objective perception improved while the lessons advanced and their experience with the other organism was intensifying. Observations consider that the learning objective was partially met, which converges with the perception of the course professor. AP
		NA: 3; 10% AP: 3, 10% A: 25, 80% NP: 0, 0%	AP (3.1)	
		NA: 0; 0% AP: 4, 13% A: 26, 84% NP: 1, 3%	AP (5.1)	
2.2 (Evaluate) Based on the MA2E4 method applied in the classroom, students should be able to evaluate and characterize materials in a	Many students came after class with questions about the material vision, so it seems this concept was not presented clearly enough. On	NA: 0; 0% AP: 5, 16% A: 25, 81% NP: 1, 3%	AP	Most students thought the learning objective was met, however, the material vision raised many questions, suggesting that it could be

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Table 18 –Triangulation

Learning Objective (Condition Actor Behavior Degree)	Overt Observations	Evaluation by the students	Evaluation by the course professor	Conclusion
sensorial, performative, affective, and interpretative dimension – aiming the creation of a vision for the project they are developing in the course, with the facilitation of a vocabulary;	the other hand, it seems that conducting the MA2E4 in the classroom enriched the students` brainwriting later;			clearer. The course professor also considered that the learning objective was partially met. AP
2.3 (Understand) Students should get to know the organism they are working with in order to develop empathy and stimulate the assimilation of operational vocabulary of the biological sciences;	It is difficult to assess how much students could learn and understand about the explanations given about *Ganoderma lucidum*;	NA: 2; 7% AP: 10, 32% A: 19, 61% NP: 0, 0%	A	Although observations could not grasp if the learning objective was met, more than half of the students ranked it as met, as well as the course professor. A
2.4 (Create) Participating in the proposed dynamics, students should be able to generate ideas of possibilities of applications by segmentation, ideas of themes, ideas of processes for their projects;	Students successfully created many ideas;	NA: 0; 0% AP: 4, 13% A: 25, 81% NP: 2, 6%	A	All three evaluations agree that the learning objective was met. A
2.5 (Evaluate) Practicing the tools proposed in class, students should be able to develop autonomy to make decisions about an application of the material and a product vision for their projects;	Students successfully made decisions about a product to be developed;	NA: 2; 7% AP: 2, 6% A: 26, 84% NP: 1, 3%	A	All three evaluations agree that the learning objective was met. A
2.6 (Apply / create) Based on the ideas generated in the	Most groups of students took more time than expected with	NA: 1; 3% AP: 8, 26%	AP	Although most of the students marked this learning objective

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Table 18 –Triangulation

Learning Objective (Condition Actor Behavior Degree)	Overt Observations	Evaluation by the students	Evaluation by the course professor	Conclusion
class brainwriting, on the repertoire presented in class and from the previous readings, the students should feel able to develop out-of-class experiments (tinkering) and record them in the project journal in a structured manner;	their tinkering activities. It seems they could not decide on what experiments to do and who would perform them. Some students let the grow-it-yourself kit spoil and did not do the tinkering experiments. However, some students developed very creative and varied experiments;	A: 22, 71% NP: 0, 0%		as met, it looks like not all of them completed the task. Also, the course professor ranked this learning objective as partially met. Maybe more time could have helped. AP
2.7 (Analyze / evaluate) Developing their sensibilities in working with other living organisms, students should be able to identify variables that impact the final outcome of their projects by tracking their development, such as the environmental conditions;	As most tinkering experiments did not happen in the expected timeframe, it seems there was not enough time for students to take their own conclusions on what variables could impact their experiments;	NA: 1; 3% AP: 10, 32% A: 20, 65% NP: 0, 0%	AP	Although most of the students marked this learning objective as met, it seems that not all of them completed the task. Also, the course professor ranked this learning objective as partially met. Maybe more time could have helped. AP
3.2 (Evaluate) Practicing the tools proposed in class, students should be able to develop autonomy to make decisions on strategic positioning and price positioning for their projects;	Students successfully proposed a pricing and market positioning strategy for their products;	NA: 2; 7% AP: 10, 32% A: 19, 61% NP: 0, 0%	A	All three evaluations agree that the learning objective was met. A
3.3 (Create) Based on the previous information and exercises, students should be able to develop design alternatives for their projects;	Students successfully developed designs for their intended products;	NA: 1; 3% AP: 2, 7% A: 28, 90% NP: 0, 0%	AP	Although the course professor marked this learning objective as partially met, 90% of the students and the observations consider it as met. A

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Table 18 –Triangulation

Learning Objective (Condition Actor Behavior Degree)	Overt Observations	Evaluation by the students	Evaluation by the course professor	Conclusion
4.1 (Understand) Students will understand the process of developing the mycelium composite raw material in a domestic (non-laboratory) context so that if desired, they can produce it independently;	It is difficult to assess if they could indeed understand how the raw material for the grow-it-yourself kit can be made at home;	NA: 0; 0% AP: 9, 29% A: 19, 61% NP: 3, 10%	AP	Although observations could not assess if this learning objective was met, more than half of the students marked it as met. The course professor considered it as partially met. AP
4.2/6.1 (Create) Consolidate a concise communication of the ongoing project, in order to move toward its realization;	Not all students presented their complete partial results – indicating that instructions could be clearer about what was to be presented. In the final presentation all items requested were successfully presented by students;	NA: 1; 3% AP: 3, 10% A: 23, 74% NP: 4, 13%	A	All three evaluations agree that the learning objective was met. A
4.3/6.2 (Understand) Students should be able to identify possibilities for improvement in the project based on received feedback;	Projects improved upon feedback;	NA: 2; 6% AP: 3, 10% A: 21, 68% NP: 5, 16%	A	All three evaluations agree that the learning objective was met. A
5.1 (Understand) Students should get to know the dynamics of one of the main digital representation tools used in the practice of design with living organisms;	Despite the discussion that the presentation of Grasshopper enabled in class, it does not seem that students could grasp the possibilities of its application in biodesign;	NA: 4; 13% AP: 17, 55% A: 7, 22% NP: 3, 10%	AP	All three evaluations agree that the learning objective was partially met. AP
5.3 (Apply/ analyze) Reflect on the pricing of the product, reassessing the initial strategy	Students successfully priced their products considering the human and material resources	NA: 0; 0% AP: 11, 36% A: 19, 61%	A	All three evaluations agree that the learning objective was met.

Table continues next page

Table 18 –Triangulation

Learning Objective (Condition Actor Behavior Degree)	Overt Observations	Evaluation by the students	Evaluation by the course professor	Conclusion
established for the project and readjusting it if necessary;	used and the product's intended strategic position;	NP: 1, 3%		A
5.4 (Apply/analyze) Reflect on the project management, comparing the planned to the executed;	Students successfully compared their time schedules, making comments on what changed in the end compared to what was planned;	NA: 0; 0% AP: 3, 10% A: 27, 87% NP: 1, 3%	AP	Although the course professor marked this learning objective as partially met, 87% of the students and the observations consider it as met. A
5.5 (Create) Students should be able to develop a communication piece for the product's promotion.	Students successfully presented a marketing promotion piece of their products.	NA: 0; 0% AP: 4, 13% A: 22, 71% NP: 5, 16%	A	All three evaluations agree that the learning objective was met. A

Source: Elaborated by the author (2023)

The next section presents insights from the immersion at Matters of Activity.

4.5.6 Insights at »Matters of Activity. Image, Space, Material«

During a 6 month sandwich period at the cluster of excellence Matters of Activity, from September 2022 to February 2023, this researcher participated in weekly events, like talks, organization meetings, reading groups, colloquiums, visited exhibitions, the annual conference, and worked at the cluster's experimental zone. Two MoA members with experience in teaching biodesign were interviewed. The immersion aimed to consider new learnings to improve and evaluate the framework, and to discuss it in an experienced international and interdisciplinary setting.

One of the events that this researcher took part in Matters of Activity was the "Frictioned Functionality. Un/Designing Un/Sustainable Matter" - MoA's first interdisciplinary Autumn School (MOA, 2022b). The Autumn School conceptually relates to this thesis in the workshop track "Designing more-than-human collaboration - Dark Fluidity: An immersive exploration of liquid ontologies in practice along the multispecies material ecologies of the river Schwärze" (MOA, 2022b). The school happened in 6 days and the description of the event was:

> Against a background of ecologies in crisis, the interdisciplinary Autumn School »Frictioned Functionality: Un/Designing Un/Sustainable Matter« invited Post-Docs, PhDs and MA students from the humanities, natural sciences and design to work through the conflicted entanglement of materiality, design and un/sustainability, using frictioned functionality as the guiding principle. In the context of this Autumn School, frictioned functionality has been understood as a working concept to reopen other narrative and performative spaces of imagination in and beyond unruly times (MOA, 2022).

The two main organizers of the autumn school were interviewed about the framework: Khashayar Razghandi and Rasa Weber. Khashayar teaches at the cluster setting in seminars and at the Master's in Open Design, and Rasa is a researcher and teaches at the Zürich University of the Arts in the Interaction Design department. At the interview, first, they were asked about their own teaching and learning practices. Later on, the framework was presented and Rasa and Khashayar offered feedback about it.

For Khashayar, the term Biodesign refers to inspiration from natural systems. Contents that he likes to emphasize are interconnectedness, ecology, performativity, dynamics – ecology is dynamic – that is the image that he wants students to take, so students should be adaptive. He says "If you want the students to be adaptive and adapt their deisign depending on the context [...] me, the teacher, should be adaptive to change my slides, my content, depending on how the course, with students being one of the actors of the course, is evolving, or is changing [...]" (transcript from the interview). Fluidity is the concept Khashayar uses for adaptivity. He summarizes his both teaching philosophies in "diversity" and "fluidity". In his teaching dynamics, Khashayar brings these concepts and tries to build a co-creation space. For each semester, his teaching is based on a specific concept, he exemplifies: "one semester was about wrinkles, another about muscles and bones, and another about growth". Around this concepts he usually calls other actors to participate, like biologists, engineers, anthropologists, designers, and cultural historians. Khashayar explains there are moments of supervision, facilitation, of accompanying the students through their projects. One technique he applies in class is the in-sito transcribing of what is happening, Khashayar writes everything that happens. With this technique, he creates a digital space that is trackable to facilitate, document, and curate the discussion. Students like it because they can follow the discussion visually, remember what was said, and have an overview of the discussion. They can see what is lacking and what topics arise.

Regarding the framework, Khashayar explained that he did not have specific feedback, but comments - some things that came up as the framework was presented. First, (I) about the design timelines, he pointed out that the activities of the project do not always follow a straight line. He exemplified that research might happen in later stages of the conceptual project and some activities of preparing a final presentation are already done at the beginning of the project. Regarding the (II) framework's contexts, Khashayar emphasized the other contexts that exist in the project: the context of the public, the field context (factory) – he explained that the public would be everything that is not happening in the classroom, in the home - everything that is not happening in these two places, but walking in the park... etc... Khashayar remarked that the boundary of these contexts would be fluid and the amount of time spent on the different things that happen in each context has an impact on the project. Furthermore, he made a comment on the moments reserved in the framework for (III) presentations. Khashayar tells that he likes to ask students to present everything they do:

"you should be able to narrate it, the things that are happening in your head, and in your making [...], to give a coherent narrative". He adds that presentations help students to reflect in and on action. Khashayar wants students to present the path which led to the final result. About the (IV) project journal, he emphasizes that what takes place is a process of translation of what happened into the journal. He explains that he understands this project journal structure as a (V) scaffold – it is good for the students to use it if they want, but they should be able to be free. Furthermore, Khashayar liked (VI) the open questions in the framework evaluation rubric. Finally, he suggested to (VII) add "place" to the "context" term because "context" could be many things.

Rasa Weber also has some criticism to the term biodesign – she explains that it seems misguided to label materials good or bad – that the hope for biodesign as a new promise to heal a broken economy seems exaggerated. She adds that it doesn`t tackle the problem of extractivism and if not handled carefully, biodesign could mean a monoculture in another way. She also points out the current lack of criticism toward the use of some materials, like fungi:

> [...] even though they are interesting as materials, they are completely brutal, because if you build a pavilion out of fungi, you would essentially kill a lot of fungi. It doesn`t mean you are not allowed to do it, but being aware of it. Being aware of the ethical constraints that you are working within and maybe the problems that you are provoking in the long run, I think this is essential to talk through with the students. (Transcript from the interview).

About her teaching practices, Rasa explains that she thinks that:

> Microalgi, for example, is something that I do believe the only way to really teach is a very hands-on approach, so I usually try to not only confront students with the end product, or the material but for example, also the means of production. Where does it come from? So, for me, it would be interesting to ask: How do you build a bioreactor, how do you grow the material yourself, under what circumstances? What do you provoque by working with a living organism? What are also maybe the risks, it entails? (Transcript from the interview).

Rasa explains that what triggered her research in the first place were the sustainability concerns. She learned from the literature that sustainability is "something that is [not] only connected to technological questions and [but] also to emotional or narrative questions" (transcript from the interview). Lately, she tries to bring a lot of literature from anthropology and biology to the students. Rasa considers that Lin Margulis, the symbiogenesis concept, and the question of evolutionary biology are essential for understanding the philosophy of ecology. Other authors that she mentions are Donna Haraway and Anna Tsing. Rasa is excited about provoking a shift in education in design – making designers design not in closed studios or laboratories, but in the environment itself. She explains that in her view, “developing something and then translating it to the open environment” does not work as a one-to-one translation. One important concept in Rasa’s research, in which she works with her students, is the concept of ecological attunement. According to Rasa:

> [...] this attunment, [is] like this very tactful or sensitive and also humble form of designing - but the first step is [figuring] developing new forms of listening, of multisensorial engagement with an environment that you don`t know yet. [...] the question is how to fill this gap of how to establish connections to an environment, how to get attuned to it – this is the field that I`m interested in – and the students are super good in this – you just have to encourage them. [...] So it is also a question of: in whose favor are you working in? (Transcript from the interview).

Rasa also talks about the discipline framing in design education. She advocates for a more open framing, without the division of what is design and what is another discipline. The idea is to frame a class around a specific theme, like water. Some questions Rasa likes to provoke in class are: “what is biotic and abiotic, what is a living material - because I think the boundaries are very blurred”. Finally, Rasa tells that she likes to bring to her students the idea of material circles and the necessity of thinking about the whole material cycle “composing materials that will eventually be decomposed”.

Concerning the feedback for the framework, Rasa points out that she thinks that (I) “the framework of Brazilian education is very different from European art schools. So, everything that you presented is super sound and solid and for me overprepared to what I would encounter with students in Europe” (transcript from the interview). She explains that she would not pre-design a grow-it-yourself kit, but she would rather leave this responsibility to the students. She argues this could bring much more interesting results in the different possibilities of substrates, for example. However, she emphasizes that the expectations of different design schools might be different. Also about the (II) templates and project journal, she tells that in the context she teaches, students like to have a greater contribution on how to design their documentation: “[...] so designing means designing all the forms of communication” (transcript from the interview). Finally, she also gives some ideas to work around the (III) space limitation, which is one of the main aspects that triggered this study. One idea would be to “[...] go out of the university when the weather conditions are good, and for example, make a dirty lab outside"; a second idea would be to connect the students' problems to scientific collaborations: "you could contact labs and establish, for example, a lab week together with them, bring the students there, and experiment in their facilities if they allow that [...]" (transcript from the interview).

All things considered, the learnings which resulted from this six-month immersion might be summarized by the following topics:

I- To encourage interdisciplinary collaborations: the cluster creates space for researchers to interact - like mediated retreats, colloquiums, working days (cluster days), and talks. People have lunch together and listen to someone giving a talk on some topic of interest for the cluster every week. Monthly planning events are organized and mediated by the management office and project leaders. Cluster members develop projects together, which result in publications, exhibitions, lecture series, and workshops. One example is the 2022 cluster retreat (MOA, 2022c);

II – To find common ground among different disciplines and new researchers: the cluster organizes mediated colloquiums for new Ph.D. candidates in the Matters of Activity Ph.D. program to figure out new projects to work together. In the colloquium, each candidate presents their own research, and later, groups are formed with the help of an experienced professor. After the teams are formed, they develop a proposal that pervades the research of all team members. As an example, the "Research Modules for the Creation, Cognition and Perception of Matter" workshop (MOA, 2023b);

III - Making connections between the existing and the new: In exhibitions and talks, the research at the cluster explores the relationship between material legacies and new material perspectives. As an example, the "Material Legacies" exhibition (MOA, 2022a);

VI – The concept of Ecological Attunement and a new design sensibility: at the already mentioned Autumn School »Frictioned Functionality: Un/Designing Un/Sustainable Matter« (MOA, 2022), Rasa Weber worked with the concept of ecological attunement with the participants. The idea of attunement was already brought up by Rasa in the interview. In another publication for Ndion (WEBER, 2023), Weber mentions the authors who previously described the concept: Vinviane Despret, Lisbeth Lipari and Karmen Franinović, and Roman Kirschner. According to this publication, ""Attunement" refers to tuning into a context" (WEBER, 2023) and it implies a new sensibility in design: "Listening to anthropocentric environments while having the courage to collaborate with them within open and chaotic systems is what constitutes the “New Sensibility” of design” (WEBER, 2023). Weber (2023) explains this involves understanding that ecological growth processes have different time spans, sometimes difficult to our human comprehension. She also points out that “not all species are ready to accept our invitation to cooperate” (WEBER, 2023);

VII- Research Through Design: “The Cluster focuses on a new role of design, which is emerging in the context of growing diversity and the continuous development of materials and visualization forms in all disciplines” (MOA, 2023a). This methodological strategy is at the core of many MoA projects. One of many examples is Emile de Visscher’s approach to developing production tools and processes and methods to work with materials (MOA, 2023c).

The insights and learnings from Matters of Activity are further discussed in section 5. The next section describes the frameworks’ contingency heuristics.

4.5.7 Framework’s contingency heuristics and generalization to a class of problems

Contingency Heuristics relate to the formalization of the artifact’s limitations considering the environment in the implementation phase, the conditions of use, and the situations in that it will be useful – it characterizes the outer environment of the artifact and its performance limits (DRESCH; LACERDA; ANTUNES JR., 2015). The contingency heuristics for this framework are described below:

I- In a public university with no access to a laboratory or studio space;

II- In the Brazilian undergraduate educational system;

III- In a Product Design course;

IV- In a class where biodesign has not been introduced before;

V- In a pedagogical context where students are less used to take more responsibility and protagonism on the learning process;

VI- During 6 weeks with 1 presential meeting per week (with an indication to happen in 15 weeks, with 1 presential meeting per week);

VII- With the availability of a classroom;

VIII- With the availability of a digital platform to upload files and communicate with students at weekly intervals;

IX- With a prepared low-cost grow-it-yourself kit;

X- With the participation of 37 students (with the indication of a limit of 40 students);

XI- With the participation of 2 lecturers/professors;

XII- With the participation of a Bioprocess Engineering and Biotechnology student in the final years (with the possibility of the participation of other students from other disciplines);

XIII- With the participation of a biodesign professional (with the possibility of the participation of more professionals with experience in biodesign).

As described by Donmoyer (2008), small sample sizes might render difficulties in generalizability in qualitative research. Thus, generalizing from a particular research setting should be a cautious move. He summarizes some arguments from other authors on that issue, defending that only consumers of a given research might be able to determine the transferability of one study to another. Donmoyer advocates that studying radically different cases "could produce enriched cognitive schema and that these schemas would allow for a kind of intellectual generalization even when settings are radically different (DONMOYER, 2008, p.372)". Considering Donmoyer's arguments, the class of problems would relate to the facilitation of teaching and learning the biodesign process (even) in a low-resource undergraduate context, meaning, even without the availability of a biology laboratory, or a space for proper experimentation in the classroom. In this sense, the framework for teaching and learning the biodesign process and the biodesign process models could be applied and tested in similar contexts – like universities, design schools, and institutions.

In the next section, the results are discussed.

5 DISCUSSION

The biodesign practice, "[...] Design and design research which use living systems as part of their production and operation" (DADE-ROBERTSON, 2021, series introduction note), seems to be consolidating through its communities (KERA, 2014; VETTIER, 2019; BDC, 2021), competitions and exhibitions (COLLET, 2013; BRAYER; ZEITOUN, 2019; MOMA, 2020; BAD, 2021), events (DESIGN MUSEUM, 2020; BIOFABRICATE, 2021; STILL ALIVE, 2020), and formal education (TUDELFT, 2023; UWA, 2022; UAL, 2022; UCL, 2022; ASU, 2022; THE UNIVERSITY OF SIDNEY, 2023; THE UNIVERSITY OF SIDNEY, 2022; UPENN, 2023; UNIVERSITY OF CINCINNATI, 2023; UNIVERSITY OF CALIFORNIA, DAVIS, 2023). Aiming to contribute to the promotion of biodesign research and practice in Brazil, this study tried to answer the question: How to facilitate teaching and learning the design process in collaboration with other living organisms (even) in a limited resource undergraduate education context? Articulated through the methodological strategy Design Science Research (DRESCH; LACERDA; ANTUNES JR., 2015), **auxiliary (I) didactic biodesign process models were developed**; **and a (II) facilitating framework for teaching and learning design in collaboration with other living organisms were created and tested.** Those two are the main contributions of this thesis and are further discussed in this chapter. Figure 46 shows the chapter overview to orient the reader.

Figure 46 – Discussion chapter overview

Chapter overview

1. Introduction	2. Design with the living concepts, and practice	3. Methodological strategy and procedures	4. Lessons on the biodesign process	5. Discussion	6. Conclusion	Appendix
				5.1 (I) Design process models 5.2 (II) Framework for facilitating the teaching and learning of the biodesign process		

Source: Illustrated by the author (2023)

5.1 (I) DESIGN PROCESS MODELS

Four design process models were underlined based on interviews: design process in collaboration with (1) mushrooms (Mush-Furf), with (2) plants – trees (Fullgrown), with (3) plants – grass (Rootfull), and with (4) bacteria (Biostudio). Seeing these models as "a representation of how things are" (DRESCH; LACERDA; ANTUNES JR., 2015, p.109), they might be understood as case studies.

It is difficult to make generalizations for all four cases because each of the projects is so unique and has more variables than the participation of another living organism. For instance, the Mush-Furf project had two teams working together: Mush was responsible for growing and testing and Furf was responsible for designing. Mycelium was not new for Mush. On the other hand, the Fullgrown project, Rootfull, and Biostudio began from scratch and developed growing and designing activities simultaneously. A distinction might also be made on how the final product is formed. While Rootfull grows the grass pre-shaping the patterns, it later harvests them to then build the artifacts – Fullgrown, Mush-Furf, and Biostudio on the other hand, grow the products directly.

The design process models are one of the main contributions of this study since the design process involving other living organisms is not often described in detail. One paper that does that is "When the material grows: A case study on designing (with) mycelium-based materials", by Karana et al. (2018). Nancy Diniz (2020b) describes the design process at the Masters of Arts in Biodesign in three main phases (see section 2.5) – but the design workflows found in the interviews in this study seem to be utterly different. In another work, Camere and Karana (2018) summarize the main phases of Growing Design based on interviews into a (1) preparation phase, a (2) growing phase, a (3) drying phase, and a (4) shaping phase. Those phases might be roughly recognized here, being most of the traditional conceptualization design tasks being addressed in the (1) preparation phase. While these design phases are described as seen in the biodesign practice, Abreu makes a whole new proposition of three different *momentums* that might repeat themselves through the design process (see section 2.5.4). The idea of a proposition of a biodesign method that makes it possible to configure the process into multiple short cycles seems interesting through the agile methodologies' lenses. According to the PMI and the Agile Alliance (2017), agile methodologies are preferred when the project has high uncertainty work, when the work was not done before and is exploratory, when the design is new, and when the complexity is high – all matching characteristics of the design process in collaboration with other living organisms (PASOLD, 2020).

In two of the cases studied in this study, the "Discover" phase from the Double Diamond did not really form a "diamond" shape, because the boundaries that would define the start of the phase were not well defined. In such cases, previous research and experiments related to the specific projects reported in the interviews had begun many years before. In all four models, the "Develop" phase from the Double Diamond was the one that took most of the project's time. This relates to the design process case studies presented by the Design Council (DESIGN COUNCIL, 2007a). According to them, this might be a sensitive part of the design process because change and bottlenecks are a possibility:

> Very often, insights from development rounds produce changes in product specifications. As development is often the most lengthy part of the design process, external factors can change too, with shifts in the market or competitor activities requiring late changes in requirements to be met (DESIGN COUNCIL, 2007a, p.22).

After the pilot - it was decided that the written results should be didactically organized by each phase: Discover, Define, Develop, and Deliver. The Double Diamond phases were chosen for such an organization instead of the PDP ones for no specific reason. Initially, one thought that there would be a correlation between the Double Diamond and the PDP phases, that they would happen in some kind of coordination, but this was not found to be true when organizing the phases according to the original models.

Often, the phases mixed up or overlapped, which was the case for the "Project Planning" phase and the "Informational Project" phase; and for the "Detailed Project" phase and the "Preparation for Production" phase. Eventually, those last two even overlapped with the "Conceptual Project" phase. In the Fullgrown project, the design process continues through what is here called "Production Follow-up", once design decisions are made while the tree grows. This phase mix-up or overlap may relate to the experimental nature of the design process with the living (CAMERE; KARANA, 2018); the new role of the designer – like its involvement in growing (OXMAN, 2015; BERNABEI; POWER, 2016; COLLET, 2017; CAMERE; KARANA, 2017; 2018; DEW; ROSNER, 2018; COLLET, 2020); and the concomitant order of some traditional design activities – like prototyping and form-giving (CAMERE; KARANA, 2018).

Camere and Karana (2018) identified that the Growing Design process would be "material-driven", where designers would begin by understanding the material. This is also suggested in the present study, where designers mostly began connecting to the other living organism (the "material"). For example, Zena Holloway understood that the grass didn't like some of the materials that could be used to make the molds; Breno de Abreu sought to know which textiles the bacteria would prefer; Furf went on an immersion with Mush to the mushroom's natural habitat; and Fullgrown learned that trees would rather prefer to grow the chairs upside-down. The authors (CAMERE; KARANA, 2018) continue that the design process would be structured in experimenting with different variables, but also intuitive. This was also the case for the interviewed projects: Fullgrown plants its plots in Gavin's very organized manner, but a lot happens intuitively: "*the branch started to push up, then you've got a lot of design decisions on how to bring the branches back and this is where you start to realize that what we are actually doing is replicating a storm, to some degree* [...]"; Zena Holloway photographs the whole process; and Biostudio uses a lab journal to keep track and plan the experiments.

Besides project documentation, it was possible to understand which design representation strategies may be applied when designing in collaboration with other living organisms. For example, Fullgrown uses Rhinoceros CAD software and also experiments in wire models. Furf works with two different software along the project, they reported that they begin in Rhinoceros, 3D modeling the final version in SolidWorks. Biostudio applies image editing software. While all those three examples rely on hand sketches as well, Rootfull develops the design alternatives directly on the material. Conversely, the design representation strategy which was cited the most in the literature review was the use of Grasshopper within Rhinoceros (OXMAN, 2014; SABIN; JONES, 2018; KIRDÖK et al.,2019; ZHOU et al., 2020; HBBE; 2021). Regarding the design representation on nano and micro-scale (NIYAZBEKOVA; NAGMETOVA; KURMANBAYEV, 2018; ANTINORI et al., 2020) – Biostudio reports the use of microscope images, but no special software as introduced by Diniz (2020a).

Time as the fourth dimension seems to have a significant influence on interspecies design collaborations (KEUNE, 2017; LI et al., 2017; DEW; ROSNER, 2018). Weber (2023) notes that ecological growth processes have different time spans, sometimes difficult for our human comprehension. Indeed, through the four interviews, it was possible to notice how the different organism's timescales influence the design timeline. Mareis writes that the literal sense of the words “project” and “design” define it, the design process, as a temporally directed activity (MAREIS, 2020). She explains that the words imply something has to be “thrown forwards” (*proicere*), and “thereby a spatial as well as temporal distance, a space of action between the present and the future” (MAREIS, 2020, p. 114, our translation). The author proceeds that “[...] many design techniques aim at making this temporally-framed space of action manageable and calculable” (MAREIS, 2020, p.114). This is the case of this study: to present design process models in negotiation with other living organisms in comparison to those models known by the students - for them to didactically juxtapose what happens to what they already understand. Hence, to better manage and calculate their own projects and practices. However, Mareis (2020) points out that it would be insufficient to see temporality in design only in the future-oriented dimension, and visual process models fail to answer the question of temporality in design:

> [...]the process of designing opens up a multi-layered and non-simultaneous, but also temporally compressed space of thought and action, in which it comes to the overlapping and confrontation of different own times of the designing. The design thus not only serves existing time models, but rather temporality is co-designed in the process of designing. [...] Characteristic for many visual process models is that they 1) segment the design process into distinct phases and 2) try to bring these phases into a coordinated time sequence. [... however] The seemingly sudden appearance of a sparkling idea thus does not take place within the framework of an organized creative process, but rather as an implicit time-and place-shifted consequence of it (MAREIS, 2020 p. 114-123, our translation).

Knowing that the models developed here will not be able to grasp all the temporal complexity in the design process - their intent does not lay on a presumption to be replicated in other space-time contingencies, rather it tries to offer a didactic representation of what happened, of “how things are [were]” (DRESCH; LACERDA; ANTUNES JR., 2015). The temporal representation is a simplification to give a visual understanding of how much each design process element “weighs” in time.

5.2 (II) FRAMEWORK FOR FACILITATING THE TEACHING AND LEARNING OF THE BIODESIGN PROCESS

The second main contribution of this study is the creation and evaluation of a framework for teaching and learning biodesign.

Almost all insights from the literature review were taken into consideration to become a requirement for the framework, from the 59 insights (Table 5), 14 were not included **due to time and resources limitations, or because they would restrict the framework contingencies** – and they are now discussed.

Insight number 5 is inspired by Ginsberg et al. (2014), Cho (2018), and Myers` (2018) discussion about the challenges of how to manage ownership of the biodesign process and the organism. This was difficult to implement in a six-week program, where hands-on activities were prioritized, along with case studies (SÖRENSEN, 2018) - but it is an important issue to bring to the educational context. Maybe one way to address it is to partner up with the university's innovation and legal department to teach students how to navigate through patents and to equip students with outlines of contract models.

Kera (2014) and Pasold (2020), present how online communities share knowledge and even ethical discussions – which inspired insight number 9 which proposes to begin an online open-source website or forum to post the student's work in a do-it-yourself format. This was also not considered a priority for the framework. In retrospect, as students' projects were at a beginner's level, it could be more interesting to recommend to them an existing platform to share their projects once and if they advance their prototyping a little further.

In insight number 10 the idea was to conduct in-class brainstorming focused on modularity across scales inspired by Diniz (MAAT, 2021), Diniz (2020b), Neeves (2018), Dade-Robertson (2021), Antinori et al., 2020), Niyazbekova; Nagmetova; Kurmanbayev, (2018), and Myers (2018). Although this insight could be implemented as an exercise within the framework, it was not prioritized because it did not converge with the pedagogical foundations – which advise open-ended assignments and working on problems proposed by the students (SÖRENSEN, 2018). Adding the constraint of working with modularity could limit the project propositions by the students.

Insight 12, the systematic approach to designing with the living was also not addressed due to a time constraint although it is widely recommended (UAL, 2022; GRUSHKIN, 2021; SABIN, 2021; DINIZ , 2020b; PASOLD, 2020; BIANCHINI; QUINZ, 2019; SABIN; JONES, 2018; PINTO; PUGLIESE, 2017). After the experience of the framework application, the recommendation to address this would be a proposition of an elective course fully dedicated to design in collaboration with other living organisms, organized into two projects: (1) one dedicated to initial experimentations and the development of a product and the (2) second one to the development of system's design with living organisms, applying system's design tools.

Insight 17 was inspired by Barnett (2020), Dew and Rosner (2018), and Collet (2017; 2020) and suggests that some activities are conducted in class for students to interact with the organism's own spontaneity. This was not added to the framework as an in-class activity because of the lack of proper space, but students could experience it to some degree in the tinkering experiments at home.

Insight 18 implies the adoption of a specific project methodology: the MBI method from Abreu (2019, see section 2.5.4), which relates to some degree to agile methodologies (PMI; AGILE ALLIANCE, 2017). This was not considered a requirement in the framework because the point was to see how students would approach the problem (SÖRENSEN, 2018). Still, the MBI method was presented to the students in class as repertoire and they could have adopted it if they wished to. In future applications of the framework, in the setting of an elective course, one of the projects could be conducted in class with the MBI approach.

Insight 43 is based on Pasold (2020), Sörensen (2018), and Pinto and Pugliese (2017) and suggests the organization of field trips to local companies and laboratories related to biodesign. In the framework application, the CEO of the mycelium Startup NeoMatter was invited to show the company's process in class. This approach was preferred because of the time constraint. It was also not included as a framework requirement because, considering the relatively low number of biodesign companies today, it seems that not all universities could have the possibility to visit a company nearby – so this would restrict the framework's contingency heuristics.

Insight 46 considers the inclusion of biomimicry into the framework's repertoire, based on UAL (2022). Whereas biomimicry relates to the biodesign content, it seems to be relatively well integrated into design curricula already.

Insight 47 considers a collaboration with the biotechnology department for students to get acquainted with professional laboratory tools (UAL, 2022). As the framework's objective is to facilitate biodesign in undergraduate education even in a low-resource context – it seemed important not to make this a requirement, considering that not all universities might have a biotechnology or biology department with a lab available. Hence this seems to restrict the framework's contingency heuristics.

Problem-first or material-first seem to be the two main starters to a biodesign project according to the literature. The Biodesign Challenge (2020), The University of Endinburgh (2022), UAL (2022), and the Universidad de los Andes (2021) - address a problem as the project starter. This inspired insight number 49. Considering the pedagogical foundation which implies the reduction of complexity (PASOLD, 2020, SÖRENSEN, 2018), the choice for the application of the framework was to work in a material-first approach (PASOLD, 2020; ZHOU et al., 2020; CAMERE; KARANA, 2018; KARANA et al., 2018; PARISI; ROGNOLI, 2017; PARISI; ROGNOLI; AYALA-GARCIA, 2016). Conversely, it was decided not to make this insight into a requirement for the framework, leaving the approach open.

Insight 50 considers the participation and organization in challenges (THE UNIVERSITY OF ENDINBURGH, 2022; THE UNIVERSITY OF SIDNEY; 2022; BDC, 2022). This was not addressed as a requirement either, leaving it open for professors, teachers, and lecturers to choose what is best for their student scenario.

Pinto and Pugliese (2017) suggest that students develop case studies (Insight 51). This was not included as a requirement because an experiential learning approach was prioritized (SÖRENSEN, 2018). However, students could present their own experiments as case studies if they wished to.

ASU (2022) has an interesting lab-rotation approach, which inspired insight 54: a project-rotation among students. This did not enter as a requirement for the framework – but it might be recommended in an advanced stage of framework application.

Finally, insight 58 implies the questions Sabin and Jones (2018) propose that could work as design requirements for a living system. Again, it was understood that this did not need to be framed as a requirement for the framework, but it would be recommended to show the questions as repertoire to the students, or even brief a project in an advanced-student setting.

Regarding the analysis of formal education in biodesign - (1) lab work; (2) reflection on ethical implications; (3) a project/studio structure; (4) interdisciplinary experience; (5) prototyping; (6) a market-driven/application-driven approach; (7) work on project communication skills; and the (8) participation on the Biodesign Challenge are emphasized on professional masterclasses, courses, undergraduate, master's and Ph.D. programs (see section 2.6.1). As previously discussed, actual (1) lab work could restrict the framework's contingency heuristics. The framework tries to tackle lab work by adapting it to be developed in the students' kitchens. This is consistent with material design, and do-it-yourself initiatives (PARISI; ROGNOLI; SONNEVELD; 2017; DIY MATERIALS, 2021; MATERIAL DESIGNERS, 2021). The reflection on (2) ethical implications were incorporated into the framework with in-class provocations and through an empathy exercise (BARNETT, 2020). Although one of the big resource issues is space, the framework focused on a hands-on (3) studio/project structure. Some project activities were conducted in the context-space classroom, and some of them were assigned to students to do in their homes. Sörensen stresses how the different learning environments impact the student's roles (2018) and a studio space at the university would be ideal. (4) Interdisciplinary experience is a challenge, mainly because of time constraints, but the application of the framework counted on the participation of a Bioprocess Engineering and Biotechnology student and the CEO of a mycelium startup company. Further collaboration ideas are discussed later in this section. The fifth highlight found in biodesign formal education is (5) prototyping. Camere and Karana (2018) presented how in "growing design" prototyping occurs concurrently to form giving, and how prototyping activities happen at the beginning of the design process. In the framework application, students were provided with a grow-it-yourself kit for tinkering and also prototyping. Concerning the highlight (6) market-driven/application-driven approach, the framework offered students marketing tools such as the perception positioning map, and cost estimation tools, which were explained in class – so they could think of their products in a production-circulation-consumption context. When students were asked when they think they learned the most in module 5, they replied it was during these activities. The seventh highlight, (7) work on project communication skills, was also addressed in the framework. Students presented their work twice during the framework application and they developed a product flyer to promote and release the product, for communicating the project they developed. Finally, the last emphasis is (8) participation in the Biodesign Challenge. As previously discussed, competitions could restrict the framework - as they have their own timeline and dynamics, with a problem-oriented approach. Participation in the Biodesign Challenge could be an advanced elective course after students were prepared with the application of the framework in a previous course.

Although Sörensen reports that "[...] less experienced students at bachelor level need clear guidance. The guidance could be a mixture of regular seminars, logbooks, and guides designed to support different stages of the explorative process" (2018, p.70) – interviewees at Matters of Activity suggested that maybe some elements of the framework could be too structured. Khashayar proposed that the project journal should be seen more like a scaffold, giving students the opportunity to work with it as they pleased. Rasa explained that her students would rather have more contributions to the project journal structure and deliverables. According to Sörensen, “The frames offer a structure to deal with unfamiliar territories and over time, the reinforced practice contributes to the development of intuitive expertise” (2018, p. 30). For future reference, it would be recommended to offer the project journal to the students, but encourage them to “tinker” with it. Rasa also noted that students could bring much more if they ought to prepare the grow-it-yourself kit themselves, she exemplified a case in her university where students prepared their own different substrates working with mycelium. This could be implemented in a longer and more advanced application of the framework - however, it would increase complexity (PASOLD, 2020). Khashayar reinforced the importance of students presenting their work. Indeed, in module 4, 7 students replied they learned the most through the partial results presentations when seeing what the other colleagues had done, and when they shared their own results.

To find common ground among disciplines and to encourage interdisciplinary collaborations the cluster of excellence Matters of Activity creates space for researchers to interact. This is consistent with the creation history of Sabin and Jones’s LabStudio (2018), which also promotes interdisciplinary cutting-edge collaborations. For a future design with the living elective courses, in a more advanced setting, it might be interesting to invite students from different disciplines and backgrounds, to make space for them to present their own research and interests and based on their presentations, to form interdisciplinary groups – similar to the dynamics in Matters of Activity Ph.D. colloquiums.

Furthermore, the concept of “ecological attunement” (WEBER, 2023), learned at Matters of Activity is of importance to the framework. According to Weber (2023), it implies a new sensibility in design: “Listening to anthropocentric environments while having the courage to collaborate with them within open and chaotic systems” (WEBER, 2023). This relates to Camere and Karana’s (2018) “new designerly sensibilities” for working in “growing design”. It relates to entering a deep empathy state with the other organism by dipping into its context through different techniques. Through the exercise of Heather Barnett and collaborators, the “small acts of being”, students exercised in some way a deeper state of empathy with the organism they were working with. In a more advanced application of the framework, it would be relevant to take students into the field, to the context where the organism lives.

6 CONCLUSION

Seeking to answer: "**How to facilitate teaching and learning the Design with the Living process in a limited resource undergraduate education context?**" - this study articulated the methodological strategy of Design Science Research to achieve (I) **didactic models of the biodesign process and a (II) facilitating framework for teaching and learning the biodesign process**. Those were accomplished through 5 specific objectives.

In phase 1 – "Problem and context", a systematic literature review was complemented with a narrative literature review to extract the relevant **concepts, emphasis, and research gaps**. This phase led to some important learnings, like many terms and concepts that are used to refer to the practice of design in collaboration with other living organisms. Chapter 2 summarizes the characterization of the design process with living materials, as well as some advice regarding the mitigation of challenges described by the authors. In addition to the traditional literature review, the educational scene for teaching and learning design in collaboration with other living organisms was also systematically studied. Other teaching and learning biodesign constellations were described, such as the Cluster of Excellence Matters of Activity.

Phase 2 – "Related artifacts" answered to specific objectives O1- To identify artifacts related to the representation and description of the biodesign process and biodesign teaching and learning; and O2- To underline didactic biodesign process models based on interviews with experienced biodesign professionals. In this phase, each piece of recommendation, concept, advice, method, model, or framework related to the biodesign process or to biodesign teaching and learning was categorized and organized into a table (see section 4.2). **Fifty-nine insights** that emerged from each item were written down and numbered in the same table. Later in this phase, semi-structured interviews were conducted **resulting in four biodesign process models to be incorporated into the main framework as case studies**. Those were elaborated based on an analysis framework built on the Mosaic Method, the Double Diamond, and the PDP models. **They visually represent the weight in time of each design task as reported by the interviewees. It is interesting to note how the life of the organism has a lot to say in the design timeline, and each organism has its special timescale**: fungi, plants, and bacteria. The design process models analysis showed that the Development phase is especially longer than the other phases. **Each project, however, had its particularities, making it difficult to draw comparisons** due to variables like outsourced activities, the maturity of the technology, and the concomitant growth of the material and the product or the harvesting of the material and consequent shaping of a product.

Phase 3 – "Development", answered to objectives O3 – To define the requirements for the teaching and learning facilitating artifact; O4- To formulate the framework for teaching and learning structure and elements; and O5- To establish an evaluation rubric for the proposed framework and its outcomes. The design of the framework began with the **59 insights** gathered in section 4.2. Most of the insights inspired **17 requirements** for the framework. Through the requirements, **21 learning objectives** were created, **upon which the framework was then outlined, as well as an evaluation rubric for its evaluation** (see section 4.4.3). The teaching/learning framework is organized into two main context spaces: the classroom, the student's homes, and the intersection in between. It is composed of 6 elements: **concepts; repertoire; project methodology; practice; reflections and management**. The framework's materialities are a project evaluation rubric (see section 4.4.5); an application script (see Table 13); a project journal (see Table 12); material samples for tests; and a grow-it-yourself kit. The framework's activities consist of presentation of concepts, case studies, and examples (the design process models); individual orientation meetings; scientific paper summarizing; ethical reflection and empathy activities; traditional design activities; tinkering and prototyping activities; market-strategy activities; management activities, and project communication activities.

Phase 4 – "Evaluation", aimed to apply the framework in an undergraduate Design teaching and learning environment; to evaluate the framework's outcomes, its instantiation; and to formalize contingency heuristics for the framework, its limitations, and possibilities, and to propose a generalization for a class of problems. Here the framework was applied in a timeframe of **6 weeks in the Materials and Processes III mandatory course in UFPR's Product Design undergraduate program**. The application script was followed, and the evaluation consisted of three steps which were later **triangulated and pattern-matched to the learning objectives: (1) Overt observation; (2) Evaluation by students (using the framework evaluation rubric); and (3) evaluation by the course professor (also using the framework evaluation rubric). The triangulation showed that 14 of the learning objectives were considered as fully met, while the other 7 were considered as partially met.** A fourth evaluation step was included to discuss the results, an immersion at the **Cluster of Excellence Matters of Activity at the Humboldt University in Berlin**. The learnings at the cluster were summarized – like the creation of interdisciplinary spaces and collaborations; making connections between material legacies and new material perspectives; the concept of ecological attunement; and the research through design approach. Furthermore, two cluster members were interviewed providing feedback for discussion. At the end of phase 4, the framework's contingency heuristics were outlined, as well as a generalization for a class of problems.

Finally, phase 5 – "Conclusion", refers to the summarization of research findings. It refers to the discussion of the results (see previous chapter) and this conclusion. The discussion of the biodesign process models began by acknowledging the difficulty to make generalizations between the 4 cases. The design phases and workflows are then compared to those found in the literature, **with the recommendation to try agile-related methodologies** in design in collaboration with other living organisms. **The PDP model and the Double Diamond model did not follow a correlation between themselves** in the developed biodesign process models. **Phases often overlapped** and this was found to be consistent with the literature. In the studied sample, **all 4 projects began with the "material"**, the other living organism. **The processes were structured and intuitive and this too corroborated what was found in the literature. Design representation techniques were also discussed, and they differed to some extent from what was found in the literature**. For instance, no special laboratory software was used, nor was the use of Grasshopper in Rhinoceros. Instead, manual sketches and prototyping with alternative materials, like wireframes, were found to be a practice. The design time scales were also discussed, as well as the limitation of the biodesign process models. The 14 insights that were not taken into consideration to build the framework were discussed, as well as the highlights from the formal education analysis in relation to the framework. **Except for the participation in the Biodeign Challenge, all highlights in formal education were addressed to some degree by the framework**. **Regarding the 14 insights which were not addressed, most of them were not included as requirements because they could restrict too much the framework's contingency heuristics, or because of time limitations.** The discussion continued with the learnings from the immersion at the cluster of excellence »Matters of Activity. Image, Space, Material«. **Through the interviews it was possible to conclude that some structures of the framework could be made mor flexible –**

for instance, the project journal could be addressed more as a scaffold and the grow-it-yourself kit could be developed by the students themselves, **leaving room for students to contribute more on the formats.** Other learnings that could be incorporated into the framework are the dynamics of creating interdisciplinary collaborations and practices that address the concept of ecological attunement.

Some of the study's limitations were already addressed in the introduction. It must be acknowledged as well, that **the sample size was relatively small**. Only 4 design process models were developed and it would be interesting to have much more. Besides that, the framework was only tested once in one specific context. In discussion with Matters of Activity members, it was noted that biodesign education in a European context would have different needs, such as a more loose and open structure, for example. It would be important to test the framework in different contexts.

The discussion led at Matters of Activity resulted in further ideas to be developed in the future. For instance, advanced applications on the framework in whole courses instead of the 6 weeks inside an existing course. The recommendation would be the creation of an exclusive elective course. The advanced applications could comprise: (1) more than one project, (2) thinking systems, (3) project rotation among the students, (4) field trips to biodesign established companies and related laboratories, (5) field trips for ecological attunement, (6) the application of agile-related methodologies like the MBI; and a (7) following special course for participation on the Biodesign Challenge with interdisciplinary students. A future development of the framework could be its reformulation according to basic essential elements and optional elements. It could be reframed in a modular structure according to the time available for its application: from one month to one semester. Additionally, there could be a parallel drawn between the framework and the Double Diamond and the PDP.

In conclusion, Myers writes that the integration of life into design will not be "free from harmful missteps, deliberate misuses, or controversy" (2018, p.10). Biodesign still presents many theoretical and practical challenges, which must be addressed with ethical discussions. Overall it seems a promising opportunity for Brazil with its biodiversity to be a protagonist in biodesign academic research and practice. **Facilitating the teaching and learning of the biodesign process for undergraduate students might contribute to promoting and diffusing this practice, even with limited resources at hand.**

One of the learnings through this research process is that designing with living organisms could be much more than designing with a material that is alive: it could be an interspecies endeavor. Many authors use the term collaboration (COLLET, 2013; BERNABEI; POWER, 2016; KIRDÖK et al., 2019; GOUGH et al., 2020); or co-performance (PARISI, ROGNOLI, 2017; CAMERE; KARANA, 2018); or co-working (COLLET, 2013; 2017; COHEN; SICHER; YAVUZ, 2019); or co-creation (CAMERE; KARANA, 2017; BERNABEI; POWER, 2016); or cooperation (KIRDÖK et al., 2019); and even co-designing (KEUNE, 2017a; 2017b; COLLET, 2020) to describe the relationships developed with the other living organism. However, those concepts usually imply that there is a common goal between the parts involved (HEEMANN; LIMA; CORRÊA, 2010). A more difficult question would be: "what does the other organism want?", Dade-Robertson asks his students: "we ask whether mycelium wants to be a brick" (2021, p.99). Vettier (2019) cites Tristan Garcia: that a living organism spends energy to defend the difference between being and not being, and as Rasa Weber explained in the interview: "because if you build a pavilion out of fungi, you would essentially kill a lot of fungi". So the relation in the design process might not be a collaboration after all, the intention still lies in an anthropocentric perspective of science, it still thinks in means to operationalize collaboration with living organisms in terms of a useful resource. One might speculate, as is the case in this study, that the hope is to lead to a respectful conscience and way of treating living organisms, and a more ecocentric attitude toward design (MELKOZERNOV; SORENSEN, 2020). Furthermore, not all biodesign initiatives kill the organism at the end, which is the case of Fullgrown – after the chair is cut from the tree, the tree will continue to grow and be shaped into another chair. Camere and Karana (2017) argue that in biodesign, designers forge the conditions for organisms to grow, which would not be there otherwise. **The issue would be how to call this interspecies endeavor.** Keune (2017a; 2017b) uses the term **mediation**. In a similar sense, Carol Collet writes that there has to be a **negotiation** of the design intention (COLLET, 2017) and Myers suggests: "Can designers learn to empathize with other forms of life and surrender a small amount of control of their work to them?" (MYERS, 2014, p.9) – **interspecies design negotiations** seems a better term to describe the relationship that happens in biodesign. We may never know the other organism's real desires, since "[...] we are only just beginning to understand the language of our collaborators" (DADE-ROBERTSON, 2021, p.9). This discussion is by no means closed.

Was the framework successful? Myers (2018), in a Frequently Asked Questions chapter, answers to "How do I know if my project is a success?" (p. 269). The author gives the reader some self-evaluation questions:

> Did this nourish your empathy for other living matter, give you more appreciation of the intricate interdependencies between species? Do you have a firmer grasp of scientific practice and how it benefits from a designer approach? Did you engage in conversations about ethics, effectiveness or possibilities working with biology (MYERS, 2018, p.269)?

In Myers' measure, the framework seems to be successful. Student's seemed to have developed "**new designerly sensibilities**" (CAMERE; KARANA, 2018; WEBER, 2023). **Sensibilities related to the acknowledgment of another, related to trying to understand this other in its own essence of existence and to negotiate form and life with it.**

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GLOSSARY

Biodesign: The University of the Arts London defines "[...] biodesign as a means to incorporate the inherent life-conducive principles of biological living systems into design processes – to transition into a more holistic, sustainable future" (UAL, 2022, p.7). Dade-Robertson uses the term biodesign meaning "[...] design and design research which use living systems as part of their production and operation" (2021, series introduction note). Myers described the term "biodesign" in 2012 as: "refers specifically to the incorporation of living organisms or ecosystems as essential components, enhancing the function of the finished work [...] dissolving boundaries between the natural and built environments and synthesizing new hybrid typologies" (2018, p.8).

Biofabrication: is a term that originates from the biomedical and biotechnological context (CAMERE; KARANA, 2018; LASVIGNES; BLISTÈNE; MADLENER, 2019; BIOFABRICATION, 2020), but is, apparently, also widely adopted by designers to describe the manufacturing process through living organisms (CAMERE; KARANA, 2017; WELLER et al., 2019; COLLET, 2020; GUMUSKAYA, 2020; MELKOZERNOV; SORENSEN, 2020; ZHOU et al., 2020). Based on other authors, Camere and Karana introduce the biofabrication concept in their work as referring to the "fabrication process of complex materials and products through organism and cell growth" (2018, p.570).

Biosynthesis: Sabin proposes the term Biosynthesis with a different connotation than the term Biomimicry (2018b). She states that Biomimicry would be a goal-oriented approach, resulting in goal-based research. On the other hand, biosynthesis would be a process-oriented approach, where solutions and applications would emerge along the process (SABIN, 2018b). She explains:

> [...] It is a mode of thinking in design generated through deep immersion within bottom-up processes found in biology and architecture[...] This type of thinking considers biological complexity and formation to emerge through code in context. Here, environment counts in the development of form. [...]. (SABIN, 2018b, p. 267).

Bottom-up and Top-down: "Notions of top down and bottom up have a range of definitions in design, but, in synthetic biology, bottom up design is seen in attempts to construct novel artificial life from scratch" (DADE-ROBERTSON, 2021a, p.60) whereas top-down design, explains Dade-Robertson, modifies existing organisms. The author explains that truly bottom-up design is yet in a very early stage.

> In reality, therefore, when we discuss bottom up versus top down, we are usually making a reference to the complexity of the organism we are working with and the degree of influence we have in defining the outcome of a fabrication process. (DADE-ROBERTSON, 2021a, p.61).

The meaning of a top-down and bottom-up process seems to be slightly different for Oxman. Nature would build artifacts in a "bottom-up" logic, while designers would take a "top-down" approach. This would mean nature parts from an adaptive response of chemical and structural material characteristics to environmental stimuli, therefore a bottom-up system. Mechanisms for this bottom-up form and function expression would be "self-organization, cell differentiation, growth, remodeling and regeneration" (OXMAN, 2015, p.100). Designers would usually start from a top-down approach, a “macro” view of the artifact - beginning by pre-establishing constraints, defining form, parts with different functions to be assembled, and then attributing materials to them (OXMAN, 2015).

Emergent behavior: Mutations are often attributed to this behavior - it would be a spontaneous response of a living organism when no information is present (in the DNA, for instance) on how to behave in the construction or assembly process of living entities (proteins, cells, etc.). Dade-Robertson explains it happens when patterns do not seem to be encoded in the biological parts themselves nor in their environment – “some information is not present in the system of assembly until the parts have assembled” (DADE-ROBERTSON, 2021a, p.47). He explains: “[...] because we cannot ask the simple question ‘Where is the information?’ since the patterning of parts gains complexity (and hence information) as the system develops.” (p.49)

Epigenetics: is the

> study of molecular processes that influence the flow of information between a constant DNA sequence and variable gene expression patterns. [...] Epigenetic processes can result in intergenerational (heritable) effects as well as clonal propagation of cell identity without any mutational change in DNA sequence (NATURE, 2007).

Besides inheriting genetic information “cells inherit information that is not encoded in the nucleotide sequence of DNA, and this has been termed epigenetic information” (GIBNEY; NOLAN, 2010, p. 4). It happens because:

> Transcription, translation and subsequent protein modification represent the transfer of genetic information from the archival copy of DNA to short-lived messenger RNA, usually with subsequent production of protein. Although all cells in an organism contain essentially the same DNA, cell types and functions differ because of qualitative and quantitative differences in their gene expression, and control of gene expression is therefore at the heart of differentiation and development. The patterns of gene expression that characterize differentiated cells are established during development and are maintained as the cells divided by mitosis. (GIBNEY; NOLAN, 2010, p. 4)

Gene expression:

> Gene expression is the process by which the information encoded in a gene is used to either make RNA molecules that code for proteins or to make non-coding RNA molecules that serve other functions. Gene expression acts as an “on/off switch” to control when and where RNA molecules and proteins are made and as a “volume control” to determine how much of those products are made. The process of gene expression is carefully regulated, changing substantially under different conditions. The RNA and protein products of many genes serve to regulate the expression of other genes (NIH, 2022)

Growing Design: is a concept by Camere and Karana (2018) considered to be a more artisanal approach in biodesign. The fabrication process is rooted in crafting, and the genetic structure of the living organisms should not be altered. Designers actively engage in growing and developing materials. In this logic, Growing Design would also include DIY materials. The material is envisioned to be used in products for the present or a probable future and not for speculative scenarios. Designers who work growing materials often compare it to traditional practices, such as making bread and beer (with yeast), as well as harvesting (CAMERE; KARANA, 2018).

***In vivo, in vitro, in silico*:** Working with another organism to produce materials in vivo means to develop the desired material qualities while the material is being formed by the organism: in vivo, or in the living. It can be made through in vitro (in the glass) control. In vitro "[...] refers to a broader notion of the human control of the chemical and physical environment" (DADE-ROBERTSON, 2021a, p.62). The author refers to these concepts as information domains: in vivo (information in the cell), in vitro (information in the environment), and in silico (information held within a computer, altering in vitro parameters) - and fabrication results depend on the interaction of both domains.

Material tinkering: it refers to "hands-on" and practical experimentation and testing with the material (PARISI; ROGNOLI, 2017). The term originates from the Human-Computer Interaction (HCI) area and means "hacking and manipulating physical interaction materials in a naive, playful and creative way [...] aims to extract data, understand material properties, understand constraints, and recognize its potentialities" (PARISI; ROGNOLI, 2017, p.67).

Morphogenesis: "in the study of multicellular organisms, the process by which cells assemble into patterns" (DADE-ROBERTSON, 2021, p.43).

Scaling analysis is a common engineering concept.

> Scaling analysis is used to either scale a process to a larger or smaller size, while maintaining the same operating conditions. For example, to design an oil pipeline, we would begin with characterizing the flow in a pilot scale pipeline 1/100th of the size of the final pipeline. In this pilot scale pipeline, we would measure the pressure drop as a function of pump rate. We would characterize these parameters in terms of non dimensional numbers. Non-dimensional numbers describe the underlying physics independent of size. In the case of pipe flow, the Reynolds number describes the flow in the pipe independent of its size. The Reynolds number is a ratio of the inertial forces (how fast the fluid is moving) to the viscous forces (how much the fluid resists flow). When we scale-up from our pilot scale pipeline that is 1 inch in diameter to pipeline that is 10 feet in diameter, we hold the Reynolds number constant. (NEEVES, 2018, p. 237).

Segmentation: Is a practice in the biological sciences to determine cellular shape. "The technique relies on the determination of boundary conditions separating the edge of the cell from its environment, typically through the use of pixel-based data originating as light" (LUCIA; SABIN; JONES, 2018, p. 221).

Templating: Templating is a key process in the Material Ecology concept (OXMAN et al., 2015). It refers to the search for patterns in nature and their simulation in a material context to create physical structures (BADER et al., 2015; OXMAN et al., 2015). "Templates are defined here as top-down material (for example, physical scaffolds) or immaterial (environmental forces) frameworks that can inform or direct bottom-up processes" (OXMAN, 2015, p.102). According to Oxman et al. (2015), Templating implies a comprehension of the material synthesis and organization logic. Templating aims to help designers to work in a top-down logic while informed by the bottom-up biological processes. The authors name different kinds of templating: (1) morphological templating, transitioning into (2) biochemical templating and culminating with (3) biological as well as (4) synthetic-biological templating.

4D printing: Li et al. (2017) and Yang, Gao, and Xu (2020) use the term 4D printing or 4D bioprinting, referring to 3D printed objects that intend some change in size, form, and/or functionality through time.

APPENDIX 1 – REFERENCE STUDIES AND QUESTIONNAIRES

QUESTIONNAIRE REFERENCE STUDY I: FABRICATING MATERIALS FROM LIVING ORGANISMS

The following text is transcribed from Camere and Karana (2018, p.582).

“List of questions asked during the interview study. Introduction & explanation of the study purpose and structure.

Phase 1 e the material.

- Can you please describe your work with (fungi/bacteria/algae) materials?

- What is this material? How do you describe it?

- For how long have you been working with it?

- Thinking also of other materials you have worked with, which opportunities and challenges do you see in this material?

Phase 2 the process.

- How does your design process unfold? Would you please draw it (here), while describing the phases, activities? You can also use samples or tools and place them on the map, or show me around in your workplace.

- Let's go in detail for some specific steps of the process: For exploration phase: what types of studies did you perform, and how did you structure them? Which was the starting purpose for the experimentation? How did you crystallize the process? How did you know you achieved a satisfactory result?

- For embodiment phase: When did the idea for a product application come into the picture? How was it elicited? User-experience wise, which challenges did you see in how the material is perceived by people?

- Do you investigate other people's perspective? How? If you wanted to do it how would you and which type of information would you be more interested in? What results would you think would be useful for your work?

- [show spider map on designers'role] How do you evaluate yourself referring to this map?

Phase 3 e purpose.

- How do you see the future role of the designer? Which will be the next steps? Please complete a second map on how you picture it changing in the next years

- What kind of awareness and considerations has this project/ material prompted you?

- How does it feel to work with this material and in this domain? How did you experience it, emotionally?

- Which are your main motivations to perform this project and work with this approach to design?

- Which ethical implications do you see in your work?

- (clarification on vocabulary, if needed) How would you describe the design phenomenon/era, which you are involved?"

QUESTIONNAIRE REFERENCE STUDY II: ELEVEN LESSONS: MANAGING DESIGN IN ELEVEN GLOBAL COMPANIES. A STUDY OF THE DESIGN PROCESS.

The following text is an excerpt with questions and references from the Eleven Lessons in Design study (DESIGN COUNCIL, 2007a; DESIGN COUNCIL, 2007b).

DESIGN COUNCIL. Eleven lessons: managing design in eleven global companies
Desk research report. London, 2007b. Available at: <
https://www.designcouncil.org.uk/sites/default/files/asset/document/ElevenLessons_DeskResearchReport_0.pdf> Accessed on March, 25, 2021.

"The study looked at the way design is used in these firms, how designers work with staff from other disciplines and how the design process is managed to deliver consistently successful results. How is design managed across complex, global, product and brand portfolios, we wanted to know. So we asked leading design teams how they select and organise their designers, and when they bring designers into the product or service development process. We also wanted to find out what skills today's designers need in order to succeed." (DESIGN COUNCIL, 2007a, p. 1)

“The remit of the study was to understand the design processes used by leading corporate users of design, what elements they involve, and how these processes take a product or service from an idea through to implementation and launch” (DESIGN COUNCIL, 2007a, p. 4)

“One of the aims of the research will be to capture and, where possible, visualise design process models in industry, as well as investigating assumptions about a small number of process models through discussion” (DESIGN COUNCIL, 2007b, p. 3).

“The key aim of this design process study was to seek the answers to five questions:
What is the design process used in leading corporate users of design?

— How is the process managed?
— What benefits does it bring?
— What are the similarities and differences among these companies’ design processes?

Are there activities or methods among the design processes observed that could constitute best practice?” (DESIGN COUNCIL, 2007a, p. 4)

— “How did design emerge as a process - what led to design being formalised?
— How did design processes develop over time?
— What models exist and what do they represent? (DESIGN COUNCIL, 2007b, p. 3).”

“in investigating the design process across several companies is taking into account how such a process will differ depending on the companies’ product or service offer, size, shape and location, legacy of design use, and its supply-chains and production systems.” (DESIGN COUNCIL, 2007a, p. 4)

“The stages of the study were as follows:

- An initial desk research project summarised the evolution and development of design process methodologies from an academic perspective, and highlighted the leading insights on areas such as the benefits of design process and best practice models. This served to inform the overall study and to aid the discussions with the design teams that were interviewed.

- Face to face interviews were conducted with the design or creative heads of eleven leading users of design.
- Prior to each interview, basic corporate data and information was gathered for each participating company. This was used both as a background for the interview, and in the formulation of the summary report and the case studies.
- The interviews were conducted by a design expert and a researcher. This, together with the discussion guide, provided both the deep understanding of design process and strategy and the robust research methodology needed to guide the collection and analysis of information from the interviews." (DESIGN COUNCIL, 2007a, p. 5)

"We have identified three key areas that will help us carry out our primary research with the 11 companies. These have been clustered through this desk research, and include:

Corporate
_ Scope of design - strategic or operational
_Influencers and motivators - people, leadership and relationships
_Skills and resources

Knowledge
_External influencers
_Information flows and dependencies
_Evaluation - testing and iterating the design process

Market
_Touch points
_Value and impact of design on brand
_Research – people & users" (DESIGN COUNCIL, 2007, pp.15-16)

APPENDIX 2 – DESIGN PROCESS INTERVIEW SCRIPT

1. PERSONAL INFORMATION – *INFORMAÇÕES PESSOAIS*

PARTICIPANT IDENTIFICATION CODE - *CÓDIGO DE IDENTIFICAÇÃO DO(A) PARTICIPANTE*:		
FULL NAME - *NOME COMPLETO*:		
DATE OF BIRTH – *DATA DE NASCIMENTO*:	CITY/ STATE/COUNTRY – *CIDADE/ESTADO/PAÍS*:	OBS:
EDUCATION - *FORMAÇÃO*:	EXPERIENCE YEARS IN DESIGN - *ANOS DE EXPEIÊNCIA EM DESIGN*:	YEARS WORKING IN BIODESIGN - *ANOS DE EXPERIÊNCIA COM BIODESIGN:*

2. DESIGN PROCESS GENERAL INQUIRY – *INFORMAÇÕES GERAIS SOBRE O PROCESSO DE DESIGN*

2.1 What changes when you design with living materials? Are there any design tasks that you changed from when you began working with living materials and now do differently?
O que muda quando você projeta com outros organismos viventes? Há alguma tarefa de projeto que precisou ser feita de outra maneira e agora você a faz de outra forma?

2.2 Do you have any tips you would give students for designing with living organisms?
Você teria algum conselho para dar aos estudantes para o design com organismos viventes?

3. CASE INFORMATION – *INFORAMAÇÃO DO CASO*

<table>
<tr><td>PROJECT NAME:
NOME DO PROJETO:</td><td colspan="2"></td></tr>
<tr><td>YEAR - ANO:</td><td colspan="2">DEVELOPMENT DURATION – DURAÇÃO DO DESENVOLVIMENTO:</td></tr>
<tr><td>ATTENDED TO A DEADLINE?
ATENDEU A UM PRAZO?</td><td colspan="2"></td></tr>
<tr><td>INDUSTRY SEGMENT:
SEGMENTO:</td><td colspan="2"></td></tr>
<tr><td>PRODUCT'S TARGET AUDIENCE:
PÚBLICO ALVO DO PRODUTO:</td><td colspan="2"></td></tr>
<tr><td colspan="3">BRIEFING OVERVIEW (did you participate in the briefing development?) – VISÃO GERAL DO BRIEFING (você participou do desenvolvimento do Briefing?:</td></tr>
<tr><td colspan="3">MATERIALS AND PROCESSES – MATERIAIS E PROCESSOS (QUE COMPÕEM A PRODUÇÃO DO PRODUTO):</td></tr>
<tr><td>PRODUCT DIMENSIONS –
DIMENSÕES DO PRODUTO:</td><td>BATCH SIZE – TAMANHO DA SÉRIE :</td><td>OBS:</td></tr>
</table>

3.1 When did the material choice come to the project?
Em que momento do projeto foi feita a escolha do material?

3.2 Was the product application already defined, or did it emerge during the project? What was the methodological approach to define the application?
A aplicação do produto já estava definida no Briefing, ou foi determinada ao longo do projeto?

3.3 How does your design process unfold? Would you please draw it, while describing the phases, tasks, design tools, and methodological strategy? Could you tell us how long each task took in days, weeks, or months?

Como o seu processo de design se desdobra? Você poderia, por favor, desenhá-lo, enquanto descreve as fases, tarefas, ferramentas de design e estratégias metodológicas? Você poderia nos contar quanto tempo levou cada tarefa em dias, semanas ou meses?

3.3.1 What and when were decisions made in each stage? Could you point them out in the drawing?
Quando e quais decisões foram tomadas em cada estágio? Poderia apontar no desenho?

3.3.2 What were the project limitations? (Budget, no gos)
Quais foram as limitações do projeto? (Orçamento, *"no gos"*)

3.3.3 Were there any risks to be considered? How were they mitigated?
Houve algum risco a ser considerado neste projeto? Como foi mitigado?

3.3.4 When were other professionals consulted?
Quando houve consulta de outros profissionais?

3.3.5 Was there teamwork? How did it happen in each stage?
Houve trabalho em equipe? Como ele ocorreu em cada estágio?

DISCOVER AND DEFINE – *DESCOBRIR E DEFINIR*

3.4 Did you analyze marketing data and competitor products? How did you do it?
Você analisou dados do Mercado e produtos competidores? Como foi a análise?

3.5 Did you conduct user research when you developed the product? What kind?
Houve pesquisa com os usuários? De que tipo?

3.6 When did you start researching the material for this project? Did you experiment yourself or was it outsourced? What kind of studies were conducted? How was the process structured?
Quando começou a pesquisa com o material para este projeto? Você conduziu os experimentos ou esta parte foi terceirizada? Que tipos de experimentos foram desenvolvidos? Como o processo foi estruturado?

3.7 How were the concept and product expression references researched for this project? Were there any trend reports informing them?
Como foi o levantamento de referências para o conceito e a expressão do produto? Houve algum trend report que informou esse levantamento?

3.8 What other kind of information did you have to gather for this project? (Ex. User-related, benchmarking, reverse engineering, outsourcing possibilities, etc.)
Que outro tipo de informações você levantou para este projeto? (Ex. Relative ao usuário, benchmarking, engenharia reversa, possibilidades de fornecedores, etc.)

3.9 How was the marketing strategy elaborated, and the product placement defined?
Como foi elaborada a estratégia de posicionamento de Mercado?

3.10 How were the first concept ideas generated and proposed? How many cycles of idea generation? Was there a special event for concept development? Who took part? How was the representation of the ideas? Were there drawings, mockups?

Como foram concebidas e geradas as primeiras ideias e conceitos? Quantos ciclos de geração de alternativas? Houve algum evento especial para essa etapa? Quem participou? Como foram representadas as ideias? Houveram desenhos ou mockups?

3.11 Were early concepts tested? How?
Ideias iniciais foram testadas? Como?

3.12 How were the selection and the approval of the final concept?
Como foi a seleção e aprovação do conceito final?

DEVELOP - *DESENVOLVER*

3.13 What happened from concept to production? Did something change in the previously defined design concept?

O que aconteceu entre conceito e produção? Alguma coisa mudou no conceito previamente imaginado?

3.14 What were the representation types used in the project until arriving to the final product? Was software used? How did prototyping and mockups happen?

Que tipos de representação foram utilizados no projeto até que se chegasse ao produto final? Foram utilizados softares? Como foi o processo de modelos e prototipagem?

3.16 How did you crystallize the material design process? How did you know you achieved a satisfactory result with the material?
Como foi consolidado o processo de design do material: Quando vocês souberam que alcançaram um resultado satisfatório com o material?

DELIVER - *ENTREGAR*

3.17 Were there any market and technical tests performed?
Houveram testes de validação técnica e de Mercado?

3.18 Were there outsourcing activities?
Houveram atividades de terceirização?

3.19 What would you have done differently?
O que teriam feito dıferente?

3.20 Where are the bottlenecks and what proved to be challenging in this project? What was difficult? Could you point them out in the drawing?

Houveram gargalos (atrasos ou dıficuldades) que foram desafiadores neste projeto? Poderia apontar no desenho?

APPENDIX 3 –CONCEPTS IN THE LITERATURE REVIEW

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 published in the last six years (from 2018 on). To compose a theoretical framework, 9 themes that could offer interesting research topics based on previous readings were defined and points were attributed to each paper according to the scheme: 0 – does not describe the theme; 1 – partially describes the theme; 2– satisfactorily describes the theme. Table 19 presents this analysis and highlights in a gray shade the studies that reached 9 points or more, which represents 50% of the total and might be interpreted as highly relevant papers. Additionally, the themes that did not achieve at least half of the total possible score, or 48 points, are highlighted. This index is called here as “theme saturation” and these topics are considered **research gaps** that could interest new studies. From those the choice was to follow the **“Design Process” theme in an undergraduate teaching and learning context**, which is justified in chapter 1, in the justification section.

Table 19 – Systematic literature review analysis

	Publication	Technology scaling/application	Collaboration	Form possibilities and shaping techniques	Design process	Production process	Design representation (sketches, virtual 3D	Aesthetics/Expression	Materials kept alive in the artifact	Material driven design	**Relevance (max 18)**
1	Antinori et al. (2020)	0	0	0	0	2	0	0	0	0	**2**
2	Appiah et al. (2019)	0	0	0	0	1	0	0	2	1	**4**
3	Attias, Danai and Abitbol (2020)	2	0	2	1	2	1	1	0	2	**11**
4	Attias et al. (2019)	2	0	0	0	2	0	0	0	1	**5**
5	Ayala-Garcia, Rognoli and Karana (2017)	0	1	0	0	0	0	1	0	1	**3**
6	Ayala-Garcia and Rognoli (2017)	0	0	0	0	0	1	2	0	2	**5**
7	Badarnah (2017)	0	0	0	1	0	0	0	0	0	**1**
8	Bader et al. (2016)	1	2	1	1	2	1	0	2	2	**12**
9	Bernabei and Power (2016)	1	1	0	1	1	0	0	1	0	**5**
10	Camere and Karana (2018)	1	2	0	2	1	1	1	0	2	**10**
11	Camere and Karana (2017)	1	2	0	1	1	0	2	0	0	**7**

Table 19 – Systematic literature review analysis

	Publication	Technology scaling/application	Collaboration	Form possibilities and shaping techniques	Design process	Production process	Design representation (sketches, virtual 3D	Aesthetics/Expression	Materials kept alive in the artifact	Material driven design	**Relevance (max 18)**
12	Cohen, Sicher and Yavuz (2019)	2	0	1	1	1	0	1	0	2	**8**
13	Collet (2017)	1	2	1	1	1	0	0	1	0	**7**
14	Collet (2020)	1	2	1	1	1	0	0	0	0	**6**
15	Dew e Rosner (2018)	0	2	1	0	2	0	0	0	0	**5**
16	Gerber et al. (2012)	2	0	0	0	2	0	0	2	1	**7**
17	Gough et al. (2020)	1	1	0	1	0	0	0	2	2	**7**
18	Gumuskaya (2020)	2	1	2	2	2	1	0	0	0	**10**
19	Karana et al. (2018)	1	1	1	2	2	1	2	0	2	**12**
20	Kera (2014)	2	2	0	1	1	0	0	2	0	**8**
21	Keune (2017)	0	0	2	0	2	0	2	2	0	**8**
22	Keune (2017)	1	2	2	1	2	0	2	2	1	**13**
23	Kirdök et al. (2019)	1	1	1	1	2	1	1	2	0	**10**
24	Lazaro Vasquez and Vega (2019)	1	0	2	0	2	0	0	0	0	**5**
25	Lee, Lee and Kim (2018)	2	0	2	0	2	0	2	0	1	**9**
26	Li et al. (2017)	1	0	0	0	2	0	0	2	0	**5**
27	Liu et al. (2017)	2	1	1	0	2	0	0	2	1	**9**
28	Melkozernov and Sorensen (2020)	1	1	0	0	0	0	1	0	0	**3**
29	Mogas-Soldevilla et al. (2015)	1	0	0	1	2	0	0	2	2	**8**
30	Monna (2017)	1	1	0	1	2	0	0	0	2	**7**
31	Moser et al. (2019)	1	0	1	0	2	0	0	2	0	**6**
32	Ottelé et al. (2011)	2	0	0	0	1	0	0	2	0	**5**
33	Oxman (2015)	1	2	1	1	2	1	0	2	2	**12**
34	Oxman et al. (2014)	2	1	2	2	2	1	0	2	1	**13**
35	Oxman et al. (2013)	2	2	2	1	2	1	0	2	2	**14**
36	Oxman et al. (2015)	1	0	0	1	1	2	0	0	1	**6**
37	Parisi and Rognoli (2017)	1	1	1	1	2	0	1	0	2	**9**
38	Parisi, Rognoli and Ayala-Garcia (2016)	2	0	2	1	2	0	2	0	2	**11**

Table continues next page

Table 19 – Systematic literature review analysis

	Publication	Technology scaling/application	Collaboration	Form possibilities and shaping techniques	Design process	Production process	Design representation (sketches, virtual 3D	Aesthetics/Expression	Materials kept alive in the artifact	Material driven design	**Relevance (max 18)**
39	Pataranutaporn, Ingalls and Finn (2018)	1	0	0	0	0	0	0	0	0	**1**
40	Sayuti and Ahmed-Kristensen (2020)	0	0	0	0	0	0	1	0	1	**2**
41	Schaffner, Ruhs and Coulter (2017)	0	0	1	1	2	1	0	2	2	**9**
42	Smith et al. (2020)	2	0	1	0	2	1	0	2	1	**9**
43	Vettier (2019)	1	2	0	1	0	0	0	2	0	**6**
44	Walker et al. (2019)	0	0	0	0	2	0	0	2	0	**4**
45	Weller et al. (2019)	1	0	1	0	2	0	0	0	0	**4**
46	Yang, Gao e Xu (2020)	0	0	0	0	2	0	0	2	0	**4**
47	Zhou et al. (2020)	2	2	2	1	2	2	0	0	2	**13**
48	Zolotovsky, Gazit and Ortiz (2018)	1	1	1	0	2	0	0	2	0	**7**
	Theme saturation (máx. 96)	**51**	**36**	**35**	**30**	**70**	**16**	**22**	**46**	**41**	

Source: Elaborated by the author (2021)

	Publication	**Concepts**
1	Antinori et al. (2020) Fine-Tuning of Physicochemical Properties and Growth Dynamics of Mycelium-Based Materials.	-
2	Appiah et al. (2019) Living Materials Herald a New Era in Soft Robotics.	Biohybrid soft robotics;
3	Attias, Danai and Abitbol (2020) Mycelium bio-composites in industrial design and architecture: Comparative review and experimental analysis.	Saprophytic fungi;
4	Attias et al. (2019) Implementing bio-design tools to develop mycelium-based products.	Bio-design; bio-fabrication; bio-composites; production scenarios; sustainable;
5	Ayala-Garcia, Rognoli and Karana (2017) Five Kingdoms of DIY Materials for Design.	Do-it-yourself; materials kingdoms; Kingdom Vegetabile; Kingdom Animale; Kingdom Lapideum; Kingdom Recuperavit; Kingdom Mutantis;
6	Ayala-Garcia and Rognoli (2017) The New Aesthetic of DIY-Materials.	Do-it-yourself; materials kingdoms; Kingdom Vegetabile; Kingdom Animale; Kingdom Lapideum; Kingdom Recuperavit; Kingdom Mutantis;

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7	Badarnah (2017) Form follows environment: Biomimetic approaches to building envelope design for environmental adaptation.	Resilience; sustainable; adaptation; biomimetics;
8	Bader et al. (2016) Grown, printed, and biologically augmented: An additively manufactured microfluidic wearable, functionally templated for synthetic microbes.	Biologically augmented; functionally templated; inform and enable; symbiotic relationship; material ecology; voxel;
9	Bernabei and Power (2016) Living Designs.	Biodesign; collaboration; co-creation; ethical issues;
10	Camere and Karana (2018) Fabricating materials from living organisms: An emerging design practice.	Biotechnology; co-performance; cradle-to-cradle; sustainability; Do-It-Yourself (DIY) materials; cross-feritilization; aliveness; programmable; agency, unpredictable; demonstrator; co-performed with nature; concurrent; intimate; bottom-up; structured; intuitive; mediators; open-minded; sensibilities, serendipity; negotiate; anticipation;
11	Camere and Karana (2017) Growing materials for product design.	Sustainability; growing organisms as collaborators; growing design; augmented Biology; digital-biofabrication; biodesign fiction; efficiency; growability; time; craft; scale; collaborative process; tinker; co-create; Do-It-Yourself (DIY) material practice;
12	Cohen, Sicher and Yavuz (2019) Designing with microbial cellulose to feed new biological cycles.	Growing design; co-worker; hackable system; Do-It-Yourself (DIY); material activism; "form follows organism"; Material Driven Design (MDD); sensorial, interpretive, affective and performative; growing system; husbandry techniques; sustainability;
13	Collet (2017) 'Grow-made' textiles.	grown-made; 'self-patterning' textile protocols; co-making; biodesign; self-patterning; bio-materiality; nature as a model; nature as a cow-worker; nature as a hackable system; designer cultivator; designer biologist; synthetic/natural nature; grow-made' versus the hand-made and the man-made; husbandry techniques; sustainability;
14	Collet (2020) Designing our future bio-materiality.	Biofabrication; husbandry techniques, cooperation; sustainability; co-designing; biodesign; nature as a model; nature as a cow-worker; nature as a hackable system; designer cultivator; designer biologist; synthetic/natural nature; husbandry principles; biofacture; biomateriality, ethical issues;
15	Dew e Rosner (2018) Lessons from the woodshop: Cultivating design with living materials.	Human-computer interaction; living materials; apprenticeship; biologically-informed; passive; discrete; entanglements; decay and resurgence; performative materials; rot; obsolescence; aging; diachronic material properties; living potential; temporal potential; digital craft materials; recuperation; collaborating with more-than-human actors; disembodied view of material engagement; "broken world thinking"; Affordance (perception of properties as a core aspect of interaction); agency; relational views, capacities for action; designer intentions; "scripts"; four-dimensional thinking; reparative expressions; vital decay, performative scarcity; rehabilitative design processes;

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		Postanthropocentric making (Devendorf); wood biography;
16	Gerber et al. (2012) Incorporating microorganisms into polymer layers provides bioinspired functional living materials.	Living material; smart material; evolutionary adaptation capacity;
17	Gough et al. (2020) The nature of biodesigned systems: Directions for HCI.	Biodesign; interaction design; interactive systems; bio-digital hybrids; Material Driven Design (MDD); synthetic Biology; interacting materials using tropisms; collaboration;
18	Gumuskaya (2020) Multimaterial bioprinting—minus the printer: Synthetic bacterial patterning with UV-responsive genetic circuits.	Biofabrication; synthetic morphogenesis; self-construction phenomenon; rule-based morphogenic acts of building; sensing and actuation mechanisms, language; bottom-up cell-to-cell interactions by design; Quorum Sensing (cell-to-cell communication);
19	Karana et al. (2018) When the material grows: A case study on designing (with) mycelium-based materials.	Material expressions; growing design; surrogate materials; material driven design; material experience; material/ micro-organism's agency; uncertainty; temporality; co-create; materials as demonstrators; design for material experience; Do-It-Yourself (DIY) material practices; material tinkering; material benchmarking; materials experience vision; material experience patterns; complex design practices; unique temporality bond; materials diary; uncertainty; sustainable;
20	Kera (2014) Innovation regimes based on collaborative and global tinkering: Synthetic biology and nanotechnology in the hackerspaces.	Synthetic biology; ethics, hackerspaces; Do-It-Yourself (DIY) bio movement; participatory turn of science studies; open science approaches; cosmopolitics; collaborative; global tinkering; materializations of the living; design as a meta-technique; prototyping; future anterior; “socially robust knowledge; upstream involvement; participatory turn; “Mode 2 knowledge production; "DIYbio grassroots projects"; citizen scientists; science diplomacy; cooperation;
21	Keune (2017) Co–designing with plants. Degrading as an overlooked potential for interior aesthetics based on textile structures.	Biodesign, co–design, human management, transforming expressions, decay;
22	Keune (2017) Transforming textile expressions by using plants to integrate growth, wilderness and decay into textile structures for interior.	Dynamic expressions; biodesign; integrate growth; wilderness; integration; maintenance; interaction; application; co-design; living technology; guided growth design process transformation over time; symbiotic relationship; the wilderness and decay expressions (aesthetics); human management; farming textiles; seasons; lifecycles;
23	Kirdök et al. (2019) Biodesign as an innovative tool to decrease construction induced carbon emissions in the environment.	Biodesign, sustainability, bio-architecture; bio-based material; biodesign; eco-construction; bio-calcification; bio-rock; bio-fabrication; cooperation; collaboration;
24	Lazaro Vasquez and Vega (2019) Myco-accessories: Sustainable wearables with biodegradable materials.	Biological Human Computer Interaction (HCI); biomaterials; sustainable;

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25	Lee, Lee and Kim (2018) Biocement fabrication and design application for a sustainable urban area.	Sustainability; Microbially-Induced Calcite Precipitation (MICP); biodesign;
26	Li et al. (2017) 4D bioprinting: The next-generation technology for biofabrication enabled by stimuli-responsive materials.	4D bioprinting; create biomimetic tissue constructs; stimuli-responsive materials; cell-laden;
27	Liu et al. (2017) Stretchable living materials and devices with hydrogel-elastomer hybrids hosting programmed cells.	-
28	Melkozernov and Sorensen (2020) What drives bio-art in the twenty-first century? Sources of innovations and cultural implications in bio-art/biodesign and biotechnology.	Bio-art; biodesign; anthropocentrism; biocentrism; converging of art and science; ethical concerns; synthetic biology; "the free inventions of the human spirit"; biofabrication; complexity, transhumanism-art;
29	Mogas-Soldevilla et al. (2015) Designing the Ocean Pavilion: Biomaterial Templating of Structural, Manufacturing, and Environmental Performance.	Biomaterial-driven design process; templating; material ecology; biomaterial structures; material-informed design; minimum inventory for maximum diversity; sustainable;
30	Monna (2017) Make the environment the (Next) Economy.	Material Driven Design (MDD); community centered cesign; Do-It-Yourself (DIY) materials; sustainable;
31	Moser et al. (2019) Light-Controlled, High-Resolution Patterning of Living Engineered Bacteria Onto Textiles, Ceramics, and Plastic.	Optogenic lithography;
32	Ottelé et al. (2011) Comparative life cycle analysis for green façades and living wall systems.	Living Wall Systems (LWS); sustainable;
33	Oxman (2015) Templating design for biology and biology for design.	Spatial and temporal scales; templating; morphological templating; biochemical templating; biological templating; synthetic-biological templating; voxel;
34	Oxman et al. (2014) Silk Pavilion : A Case Study in FIbre-Based Digital Fabrication.	Generative design; template; sustainability;
35	Oxman et al. (2013) Biological Computation for Digital Design and Fabrication.	Design generation; biological and digital optimization; biological process as form of computation;
36	Oxman et al. (2015) Material ecology.	Material ecology; sustainable;
37	Parisi and Rognoli (2017) Tinkering with Mycelium. A case study.	Material tinkering; intimate material dialogue; material agency; co-performing; prototyping;
38	Parisi, Rognoli and Ayala-Garcia (2016) Designing materials experiences through passing of time - Material driven design method applied to mycelium-based composites.	Time passing and design; sustainability; Do-It-Yourself (DIY); material experience vision; manifesting the material experience pattern; designing the material concept; intangible characteristics of materials; intangible sparks; low-tech; Material Driven Design (MDD);
39	Pataranutaporn, Ingalls and Finn (2018) Biological HCI: Toward integrative interfaces between people, computer, and biological materials.	Biological HCI, biology, biotechnology, biodesign, interface, tangible interface, speculative design; ethical debate;

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40	Sayuti and Ahmed-Kristensen (2020) Understanding emotional responses and perception within new creative practices of biological materials.	Biophilic design, biodesign, biological materials, emotional design, perception in design;
41	Schaffner, Ruhs and Coulter (2017) 3D printing of bacteria into functional complex materials.	Bacteria-derived functional material; biocompatible; biofilms; direct ink writing; Flink; functionalization;
42	Smith et al. (2020) Hybrid Living Materials: Digital Design and Fabrication of 3D Multimaterial Structures with Programmable Biohybrid Surfaces.	Living/non-living composite materials; biohybrids; spatiotemporal functions; biological templating; voxel (volumetric material description, decoded by the printer in physical droplets);
43	Vettier (2019) Biodesign, comment penser la production avec le vivant?	Biodesign; synthetic biology; biotechnology; living matter; ethics; rhythm, transformation, critic design; critic and speculative project dimensions;
44	Walker et al. (2019) Engineered cell-to-cell signalling within growing bacterial cellulose pellicles.	-
45	Weller et al. (2019) Mycelium artifacts: Exploring shapeable and accessible biofabrication.	Sustainability; accessible; biofabrication;
46	Yang, Gao e Xu (2020) Recent Advances in 4D Bioprinting.	4D bioprinting; cell-laden living systems; bioconstructs;
47	Zhou et al. (2020) Digital biofabrication to realize the potentials of plant roots for product design.	Biodesign (new industrial paradigm); sustainable; material-driven design; diy design parameters; discrete porous structures; digital biofabrication; co-creation; template; symbiotic approach; hybrid/composite; affordances; boundaries; living; non-living; manmade; computational intelligence; biological intelligence ;
48	Zolotovsky, Gazit and Ortiz (2018) Guided Growth of Bacterial Cellulose Biofilms.	Bio-hybrid; material patterning; biological responsiveness; hierarchical self-assembly; sustainable;

Source: Elaborated by the author (2021)

APPENDIX 4 – ABREU`S GLOSSARY

(ABREU, 2019, pp. 176-179)

Anaeróbico: Organismo que cresce na ausência de oxigênio.
Artefato: pode ter diversos significados para diferentes áreas, mas aqui designaremos como um produto, objeto ou processo originário do trabalho humano, seja lá qual for a sua natureza.
Biofilme: comunidade de microrganismos dependente de densidade celular que se desenvolve na superfície dos meios de cultura, envolta por material aderente de natureza polissacarídica.
Bioinspiração: qualquer ideia ou artefato que tenha como inspiração algum elemento da natureza, podendo ter ou não em sua constituição final o próprio elemento orgânico.
Biologização: transformação de processos diversos sejam eles mecânicos, eletrônicos, digitais, dentre outros em processos biológicos ou relacionados e inspirados na natureza.
Cepas: cepas ou estirpes são grupos de organismos que descendem de um ancestral comum, compartilhando assim características morfológicas (forma) ou fisiológicas (funções mecânicas, físicas ou bioquímicas).
Ciborgue: qualquer organismo híbrido, que passe por um processo de alteração de suas capacidades por meio de processos tecnológicos.
Comunidade: duas ou mais populações de organismos que convivem no mesmo lugar, ao mesmo tempo.
Contagioso: que transmite algo. Sua utilização quando relacionada à biologia na contemporaneidade, tem uma associação com doenças transmissíveis, mas outros elementos abstratos podem ser contagiosos, como o sorriso, a memória, a raiva, o afeto.
DNA: polímero de desoxirribonucleotídeos unidos por ligações fosfodiéster que carregam a informação genética.
Esporo: termo genérico dado a estruturas resistentes de dormência celular, ou seja, espécies de "sementes" de procariotos e fungos que podem sobreviver muito tempo no ambiente em estado de dormência, voltando a germinar e produzir uma célula filha ao encontrar um ambiente favorável para o seu crescimento. Existem relatos de esporo com séculos de existência em ambientes áridos que voltaram a germinar quando em contato com meios de culturas favoráveis a seu desenvolvimento.
Eucarioto: célula ou organismo que apresenta núcleo envolto por membrana e que geralmente apresenta organelas.
Fagocitose: Processo no qual a partícula exógena de alimento é englobada pela membrana plasmática, sendo conduzida ao interior da célula, onde é digerida. 177

Fatores sensíveis: são aquelas características presentes nos microrganismos que chamam a atenção de algum de nossos sentidos, seja a visão, paladar, tato, olfato ou mesmo audição.
Fenótipo: são as características visuais aparentes dos microrganismos, como cor, forma ou motilidade (movimento).
Fitoplâncton: é formado pelas algas, cianobactérias ou arqueias que vivem em suspensão na água, mas com movimentação restrita, podendo ser fotossintetizantes. O fitoplâncton tem uma importância muito grande, gerando cerca de 70% do oxigênio da atmosfera terrestre, estando também na base da cadeia alimentar dos ecossistemas aquáticos.
Geosmina: substância química caracterizada como o cheiro de chuva que é produzida por alguns microrganismos, como as bactérias *Streptomyces coelicor.*
Hospedeiro: organismo que permite e viabiliza o crescimento de um parasita.
Infecção: invasão, crescimento e multiplicação de um organismo no interior de um hospedeiro, que reage de diversas maneiras.
Interator: usaremos a palavra interator para designar o observador ativo de um artefato, que não apenas vê, mas interage de diferentes maneiras com o artefato, dando continuidade aos processos criativos e reflexivos do autor.
Máquinas autopoietica: máquinas que continuamente produzem a si mesmas por meio da produção de seus constituintes, sob uma constante de desequilíbrio e reequilíbrio.
Meio de cultura: solução composta pelos nutrientes necessários para o crescimento e desenvolvimento dos microrganismos. Sua composição e disponibilização de substâncias são essenciais para o desenvolvimento dos microrganismos. Já os meios de cultura dos humanos, envolvem muito mais que nutrientes, mas uma complexa rede de maneiras diferentes de nutrição. Meio de cultura é uma expressão que abre precedente para pensarmos em várias analogias, afinal o meio de cultura alimenta a todos, não somente as bactérias.
Metabolismo: todas as reações de transformações de substâncias químicas que ocorrem em uma célula ou em um ser vivo, sejam elas de construção ou quebra. Muitas metáforas podem ser feitas com o metabolismo, mas sempre significando processos antagônicos de produção e destruição que ocorrem dentro de um dado organismo.
Microbiota: uma microbiota equilibrada é formada pelo conjunto de microrganismos que vivem em harmonia na superfície, no interior do nosso corpo e até no interior das células, possibilitando uma vida saudável.
Micrômetro: normalmente a unidade de medida utilizada para os microrganismos é o micrômetro (µm). 1 mm = 1000 µm. [178]

Momentum: Apresenta dinamismo, movimento; que tem ação de uma força, um impulso. É um dos ciclos, uma macro etapa, do Método Microbioinspirado, que apresenta três Momentums, o Momentum Rep, o Momentum Cell e o Momentum Morf.
Micróbio: os termos micróbio e germe surgiram no século XIX, quando a tecnologia disponível não permitia a diferenciação dos microrganismos. São termos mais pejorativos que tem uma associação direta com doenças. O termo micróbio, no entanto, será aqui utilizado algumas vezes para substituir a palavra microrganismo para que não ocorram tantas repetições, mas sem nenhum teor pejorativo.
Microbioinspiração: qualquer ideia ou artefato que tenha como inspiração um microrganismo, podendo ter ou não em sua constituição final o próprio microrganismo.
Microbiota: conjunto de microrganismos que estão associados a diversos tecidos ou órgãos de seres vivos quando em seu estado saudável.
Mutação: alteração hereditária na sequência de bases de um gene de um organismo. A mutação pode acontecer de maneira espontânea ou induzida.
Organelas: são estruturas membranosas que apresentam funções específicas na célula. Mitocôndrias: são organelas responsáveis pela realização da respiração celular, constituindo a principal fonte de energia nas células não fotossintetizantes; já os cloroplastos são organelas que apresentam clorofila, sendo responsáveis pela fotossíntese.
Parasita: organismo que sobrevive associado a um hospedeiro, causando-lhe malefícios diversos.
Procarioto: célula ou organismo desprovido de núcleo e de organelas membranosas.
RNA: polímero de ribonucleotídeos unidos por ligações fosfodiéster que apresenta função essencial na produção de proteínas.
Quorum sensing: é um sistema de regulação dependente da densidade populacional. É conhecido também como uma forma de comunicação química que pode acontecer dentro de uma população de microrganismos quando ela atinge alta densidade demográfica, podendo acontecer ainda entre espécies diferentes de organismos. Um exemplo do Quorum sensing pode ocorrer quando temos uma densidade populacional muito grande e os indivíduos começam a sinalizar a necessidade de se produzir algum antibiótico para a sobrevivência coletiva da espécie, evitando a proliferação de outro microrganismo no meio de cultura.
Raiz: é o órgão da planta responsável pela fixação a um substrato e pela absorção de água, nutrientes e minerais. Alguns microrganismos vivem ligados às raízes como simbiontes, numa relação mutualística, onde os dois seres se beneficiam. Metaforicamente, as raízes fazem referência à origem, ao princípio, à base e também a fixação e imobilidade. 179

Simbiose: é uma relação entre dois organismos, que geralmente se desenvolve em longo prazo e evolutivamente, podendo ser positivas para ambos, neutras ou negativas. Metaforicamente a simbiose também pode ser desenvolvida entre seres humanos e nas suas relações cotidianas, mas de maneira leviana ou em longo prazo, dependendo das relações estabelecidas entre as partes.

Teoria da Complexidade: propõe a indissociabilidade dos fenômenos e a abordagem multidisciplinar para a construção do conhecimento.

Trato gastrointestinal: O trato gastrointestinal varia muito de estrutura nos vertebrados, mas na grande maioria a absorção dos nutrientes acontece no intestino delgado. Já a fermentação microbiana pode acontecer em estruturas como o pré-estômago, ceco ou intestino grosso.

Ubiquidade: é a faculdade de estar presente em todos os lugares. No caso dos microrganismos, é a capacidade de estar presente em muitos diferentes habitats da Terra, como acontece por exemplo com as bactérias de solo que estão presentes em quase todo o mundo. A partir do desenvolvimento das tecnologias digitais e da rede, o conceito de ubiquidade foi relativizado.

APPENDIX 5 – PAPERS AND PUBLICATIONS

1-STROBEL, E. do N.; HEEMANN, A. . Perspectivas em design e materiais vivos: discussão da literatura. In: Gampi + Plural Design 2020, 2020, Joinville. Anais Gampi + Plural Design 2020. **Anais...** Joinville: Editora Univille, 2020. p. 240-253.

Abstract: There are different approaches for designing with living materials, which involves the participation of other organisms to develop artefacts. However, this is still considered an experimental practice and the materials agency poses many theoretical and practical challenges. In this paper, we contribute by systematically reviewing the scientific literature to find emphasized design concepts and practices with living materials, as well as possible research gaps. After the analysis of 33 papers, we identified four themes that we discuss: terminology, collaboration, the materials time dimension and material aesthetics. We also present the different approaches we found on product design with living materials. We conclude describing the possible research gaps for future developments.

Keywords: Living materials, biofabrication, design concepts.

2*- NASCIMENTO, E. S. do; LAU, G. M. ; ISHIY, F. C. ; HEEMANN, A. . Design com materiais vivos: reflexões sobre ensino de projeto e novas sensibilidades. In: Gampi + Plural Design 2020, 2020, Joinville. Anais Gampi + Plural Design 2020. **Anais...** Joinville: Editora Univille, 2020. p. 285.

3 - NASCIMENTO, E. S. do; LAU, G. M. ; ISHIY, F. C. ; HEEMANN, A. . Design com materiais vivos: reflexões sobre ensino de projeto e novas sensibilidades. Design com materiais vivos: reflexões sobre ensino de projeto e novas sensibilidades. **Plural Design**, v. 4, p. 80-90, 2021.

Abstract: Design with living materials brings new project dynamics and sensibilities, shown by the literature. In this article we wanted to know how students from undergraduate degree in Design would approach projects with living materials without a given methodologic strategy. The aim was to collect their spontaneous perspectives, perceptions in relation to other projects with traditional materials and discuss the sensibilities according to the literature. The study took place in the Studies in Design and Living Materials course, 6 teams of undergraduate students proposed 12 product concepts with fungi and plants. The discussion brings the students perspectives on the method, the reflections on the uncertainty about the materials agency, and related to the lack of experimentation with the material. The conclusion shows opportunities to explore different methodological approaches, representation strategies and experimentation to build new design sensibilities to communicate to the material and to observe and collaborate with it with an informed eye.

Keywords: Living materials, biofabrication, project development.

4*- NASCIMENTO, E. S. do; LAU, G. M. ; ISHIY, F. C. ; HEEMANN, A. . Design e materiais vivos: perspectivas e aplicações da celulose bacteriana no design industrial, arquitetura e moda. In: ENSUS “Encontro de Sustentabilidade em Projeto” (IX.: 2021 : Florianópolis, Anais [do] ENSUS 2021 - IX “Encontro de Sustentabilidade em Projeto”/ Universidade Federal de Santa Catarina, realizado em 19, 20, 21 e 28 de Maio de 2021, 04 e 11 de Junho de 2021 **Anais...** v.9, n4., 2021. p. 19-30.

5- DO NASCIMENTO, ELISA STROBEL; LAU, GISLAINE MARIA; ISHIY, FELIPE DE CARVALHO;HEEMANN, ADRIANO. Materiais vivos, o caso da celulose bacteriana: revisão bibliográfica da aplicação no design industrial, arquitetura e moda. Mix sustentável (print). , v.7,p.71 - 82, 2021.

Abstract: Design with living materials, when other organisms take part in the artifact's development and production, unveils new possibilities, theoretical and practical challenges. This research focuses on design with bacteria and aims to identify and map applications and perspectives for bacterial cellulose in industrial design, architecture and fashion. Through systematic literature review, we analyzed 27 academic works and 16 national and international patents. We found an emphasis on fashion and textile purposes and a focus on growing, molding and finishing processes. Finally, we present the difficulties for this material and discuss opportunities for designers.

Keywords: Biodesign; Living Materials; Biofabrication; Bacterial Cellulose

*These papers were also selected to be expanded and later published in special editions in journals – the references for those publications will be added later.

APPENDIX 6 – BIODESIGN CHALLENGE EVALUATION RUBRIC

1.	CONCEPT (The idea)	1.1 ORIGINALITY Is the project original? Does it approach the chosen topic in an innovative way? 1.2 DESIGN How effectively does the project respond to the topic the team posed? 1.3 FEASIBILITY -A. Scientific: How well has the team demonstrated that trends in current science indicate that their vision will be possible? -B. Cultural: How deeply has the team considered whether biotech is the most appropriate response to this issue, as opposed to other technologies or social solutions? Has it considered how this vision fits into or replaces already-built cultural and material systems?
2.	PRESENTATION (Communicating concepts)	2.1 VIDEO PRESENTATION Each team is expected to submit a 5-10 minute video for the Summit. The video should explain how the project functions, the subject it addresses, the science behind it, how it may be adopted, and the process by which the team arrived at the idea. Teams must create visual renderings that capture the look, functionality, and possible uses of their project. We encourage students to be creative with the presentation. 2.2 LIVE DIALOGUE Following the video presentation, students will be asked to discuss their projects with the judges for 5-8 minutes. Teams will be evaluated on how well they respond to the judges. Students should be prepared to ask for feedback on specific aspects of their project. 2.3 WEBSITE (RECOMMENDED – JUDGES WILL NOT SCORE THIS COMPONENT) Teams are urged to create a website that describes their project. This site can serve as a record of their work, a place to highlight team members' biographies, achievements, and future goals. 2.4 SOCIAL MEDIA (RECOMMENDED – JUDGES WILL NOT SCORE THIS COMPONENT) We ask students to actively participate in promoting their projects online by developing creative social media campaigns. We recommend making use of Instagram, Twitter, Facebook, and LinkedIn, but teams are welcome to post on the platforms they prefer. We ask teams to tag @biodesigned where possible.
3.	REFLECTION	3.1 PROCESS How much experimentation and exploration has the team done and how well has this been communicated in the presentation? Did the team identify new questions during the process? 3.2 SELF APPRAISAL Has the team recognized strengths and weaknesses to its vision? Has it suggested ways to address them? What are next steps? Has the team recognized all the voices—experts and otherwise—necessary to inform the project?
4.	CONTEXT	4.1 HUMAN IMPACT A. Users/Nonusers/Scalability: How deeply has the team considered how the design changes the lives of those who use it and those who don't use it? These might include workers involved in its manufacture as well as those who don't have access to the design or can't afford to pay for it. Has the team considered how

Table continues next page

widely its design might be used, including among different genders, races, and socioeconomic groups?

B. Ethics: How well has the team considered ethics imbued in their vision? Does its vision challenge or reaffirm the ethics of those for whom it's meant and/or those by which it was created?

4.2 SUSTAINABILITY
A. Environmental Impact: How deeply has the team considered its design's interaction with living environments? How might the project change the living environment? For good, bad, both?

B. Efficiency/Life Cycle: How well does the project consider the use of resources (e.g. water, feedstocks, energy, labor, etc.)? Has the team considered their design's entire life cycle? How is it sourced? Can it be recycled or reused in other ways?

4.3 RISK
Has the team considered the potential negative effects of its vision?

A. Safety: Has the team accounted for possible harm to human health and the living environment associated with its product or process malfunctioning? Has the team changed their design to mitigate these risks?

B. Dual use: In the hands of someone with ill intent, any design can be used nefariously. Has the team considered how their design might be harnessed for ill intent? Has the team considered how its design could be negatively exploited, and how to mitigate that risk?

APPENDIX 7 –STUDENT'S PROJECT RESULTS AND EVALUATION

Miel – Students A1, A3, A32 and A10

Miel is a beehive with a modular design. The students' design vision is: "The product aims to encompass the universe of bees, creating a welcoming structure for their hive and its particularities. The modularity of the product enables access to the hive. Produced from mycelium, the product relates to the natural aesthetics of the bees and meets certain needs, such as thermal protection. The aesthetics of the product seeks to enhance the identity related to the animals, inserting them in a relationship of mutualism between the urban and the natural, with the aim of naturalizing urbanity and not the opposite" (By the students, our translation).

The team planned a ludic and natural aesthetic for the project, the final product should cost 250 reais in their market positioning exercise. A highlight of the project was an empathy map for the bees. Four products would have to be sold to cover prototype development costs. Students had time difficulty producing the final prototype, it was not ready until the end of the final delivery. A rendering and the beginning of the prototyping process are represented in Figure 47.

Figure 47 – Miel rendering and prototype production

Source: elaborated by the students (2022)

Figure 48 presents the evaluation for all four evaluators in every category. The team got mostly “Excellent” ratings, except for the “Time management” category.

Figure 48 – Evaluation of the Miel project

Source: Elaborated by the author (2022)

Lumi – Students A4, A5, A13 and A27

Lumi is a lamp. The students' design vision was: "From the previous activity, we understood that we wanted to bring the irregularity and the handmade appearance to the product, showing that it is something unique and that it can become an affective object to the person who owns it. Moreover, with the conclusion of the characteristics we observed the possibility of creating a product that speaks to more than one type of material, because at first the living material causes a strangeness by the unfamiliarity, so the product will be [made of] mixed [materials] and we will work on the positive points that caught our attention, such as opacity, resistance and the final texture of the material." (By the students, 2022 our translation).

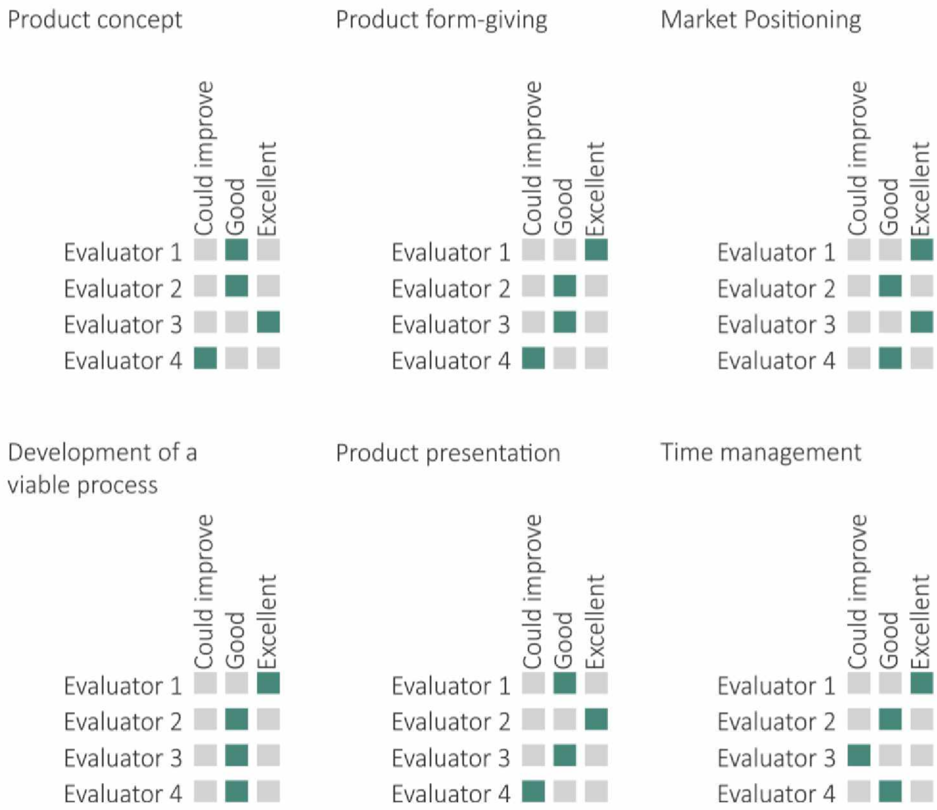
Their design was positioned among "rustic" and "alternative" The estimated price was 500 reais. Time was also an issue for this team, which also did not present the grown prototype. Figure 49 presents a representation of the design and the team's prototyping process. The students reported their difficulty in making a good design representation, due to their lack of personal skills.

Figure 49 – Lumi rendering and prototype production

Source: elaborated by the students (2022)

Figure 50 presents the evaluation of the Lumi project according to each evaluation category. It received mainly “good” ratings.

Figure 50 – Evaluation of the Lumi project



Source: Elaborated by the author (2022)

Monarc – Students A6, A22, A25 and A33

For the Monarc project, the design vision was: “The team aimed to study organic shapes, alluding to the theme "Time". In this way some products that could be developed by the team were considered, among the main ones, vases, and lamps” (by the students, 2022, our translation). Ultimately, the team decided to design a jewelry collection inspired by the life cycle of the Monarc butterfly.

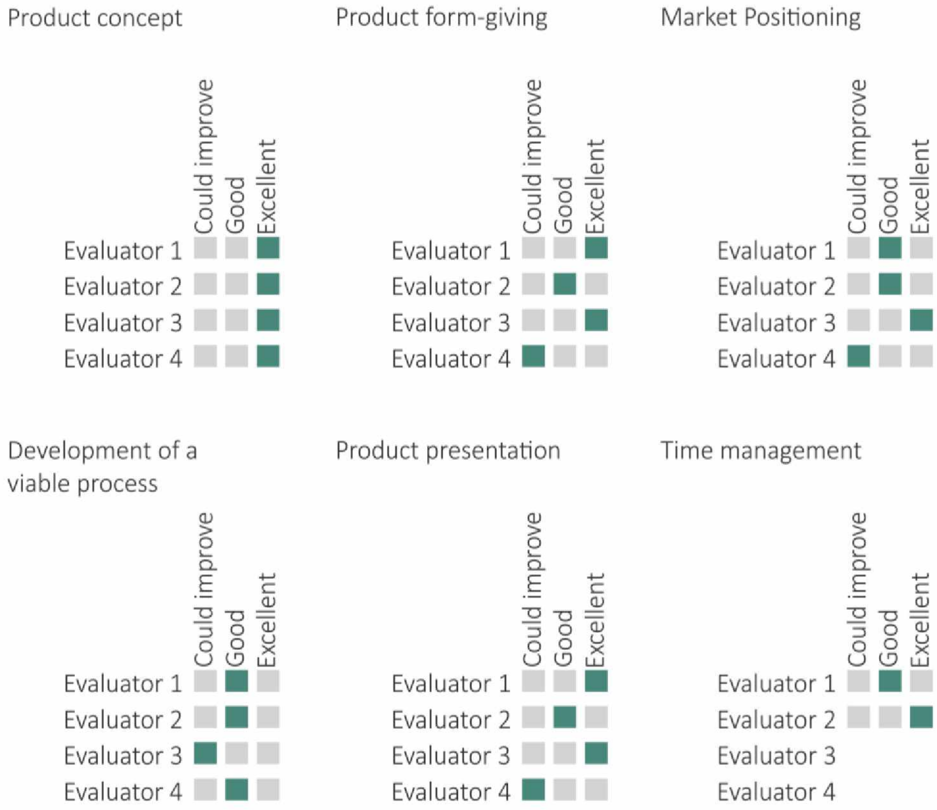
The students defined a price for the set of about 1.215 reais but did not develop a perception positioning map. The team reported that the time constraint was their main difficulty. Figure 51 presents a digital representation of the designs and the development of the prototype.

Figure 51 – Monarc rendering and prototype production

Source: elaborated by the students (2022)

Figure 52 presents the project ratings by the four evaluators. The team received mainly “good” and “excellent” ratings.

Figure 52 – Evaluation of the Monarc project



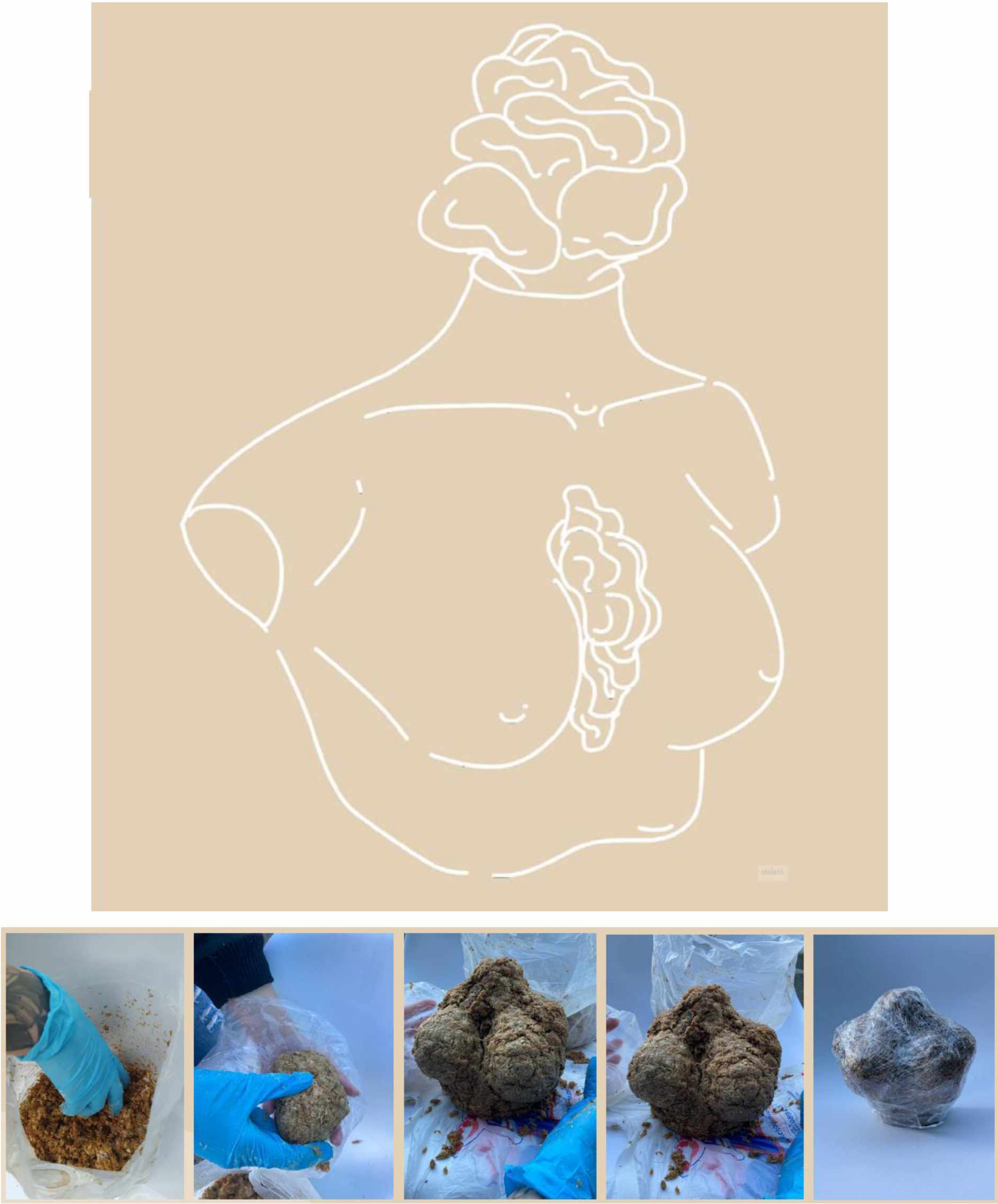
Source: Elaborated by the author (2022)

Sculpture – Students A34, A24 and A35

This team's project was a sculpture design. The team did not organize a design vision, but they underlined the materials' qualities: "Lightweight material; High strength when thicker; The part in contact with the mold is softer + oxygen; Depending on the forming process, it is more fibrous; and it arouses curiosity and questioning because it seems to be heavier, but although light, it is resistant" (by the students, 2022, our translation).

The feminine was the project's main theme and the expectation was to have some parts of the mycelium kept alive and constantly growing. In the perceptual positioning map students aimed at "Transformation" and "organic shapes" concepts. It is not clear what price the team aimed for the final product. Figure 53 presents a sketch of the design and the prototype development.

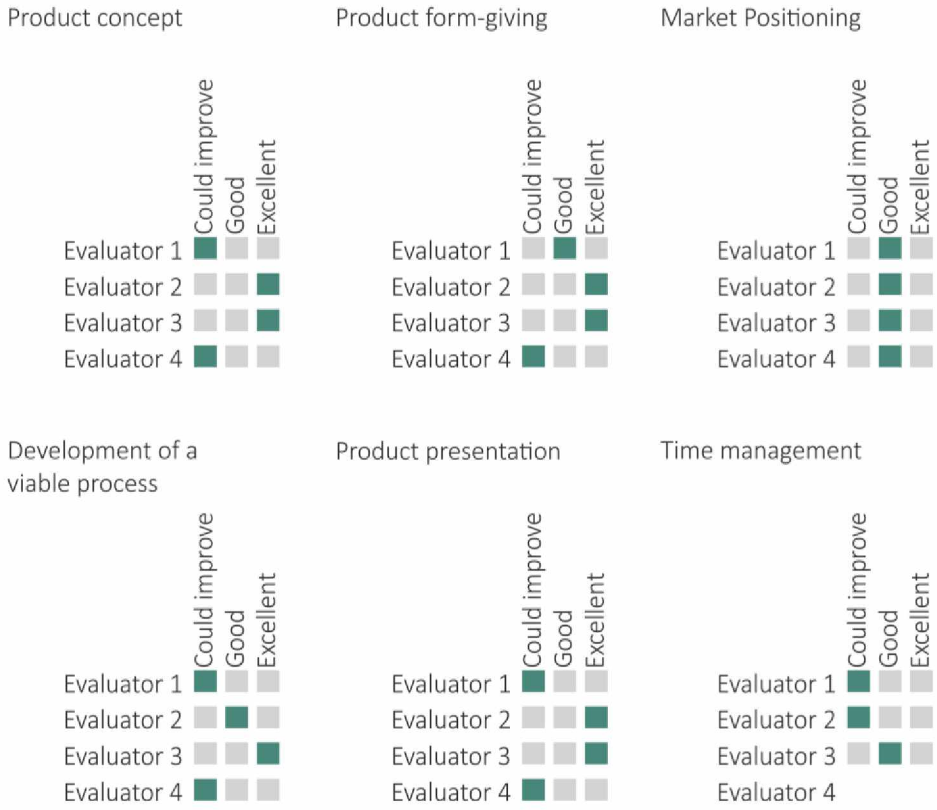
Figure 53 – Sculpture sketch and prototype production



Source: elaborated by the students (2022)

Figure 54 shows the ratings by the four evaluators for this project.

Figure 54 – Evaluation of the Sculpture project



Source: Elaborated by the author (2022)

Caetés – Students A2, A12, A20 and A30

This team did not write the design vision in detail, they mention: “To be a product that is unique compared to those already on the market, and that can be found in retail stores."Free" shapes that make the customer buy a unique product” (by the students, 2022, our translation).

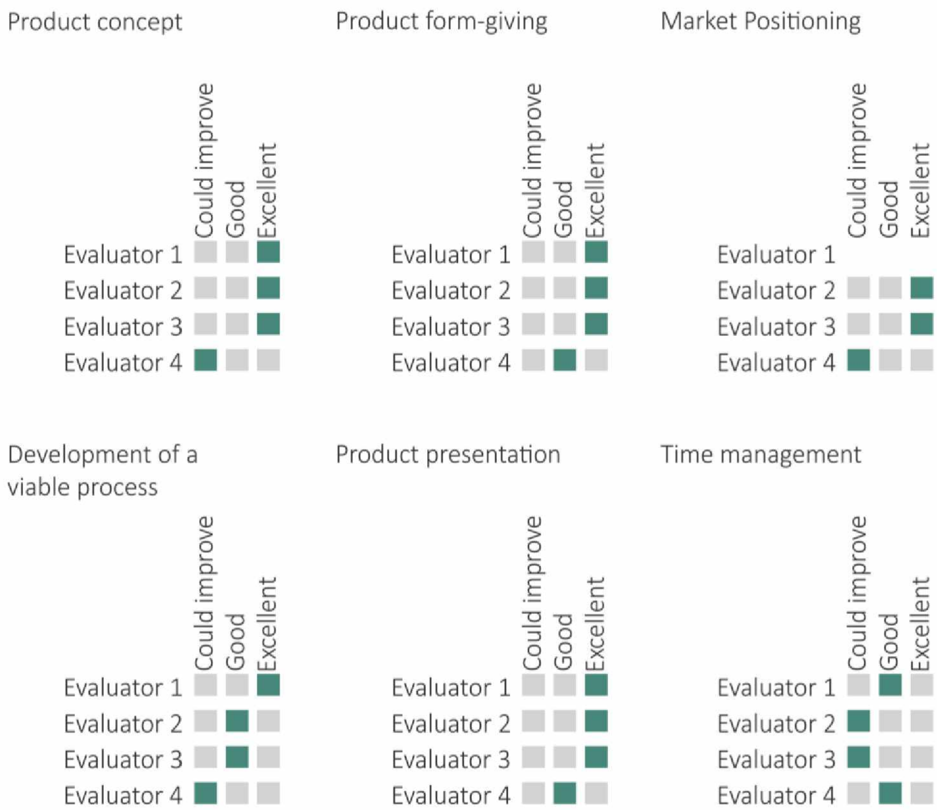
The team did not develop a perceptual positioning map, the estimated product price is 400 reais. Figure 55 presents the product rendering.

Figure 55 – Caetés rendering

Source: elaborated by the students (2022)

Figure 56 presents the ratings for the project, which were mostly marked as “excellent”.

Figure 56 – Evaluation of the Caetés project



Source: Elaborated by the author (2022)

Filó – Students A14, A36, A18 and A21

The Filó project is about a jewelry collection with an underwater theme, the design vision was: "Sustainability, simplicity, coziness, awareness" (by the students, 2022, our translation).

The team did not write about the concept in detail The product's estimated price was 7,70 reais.

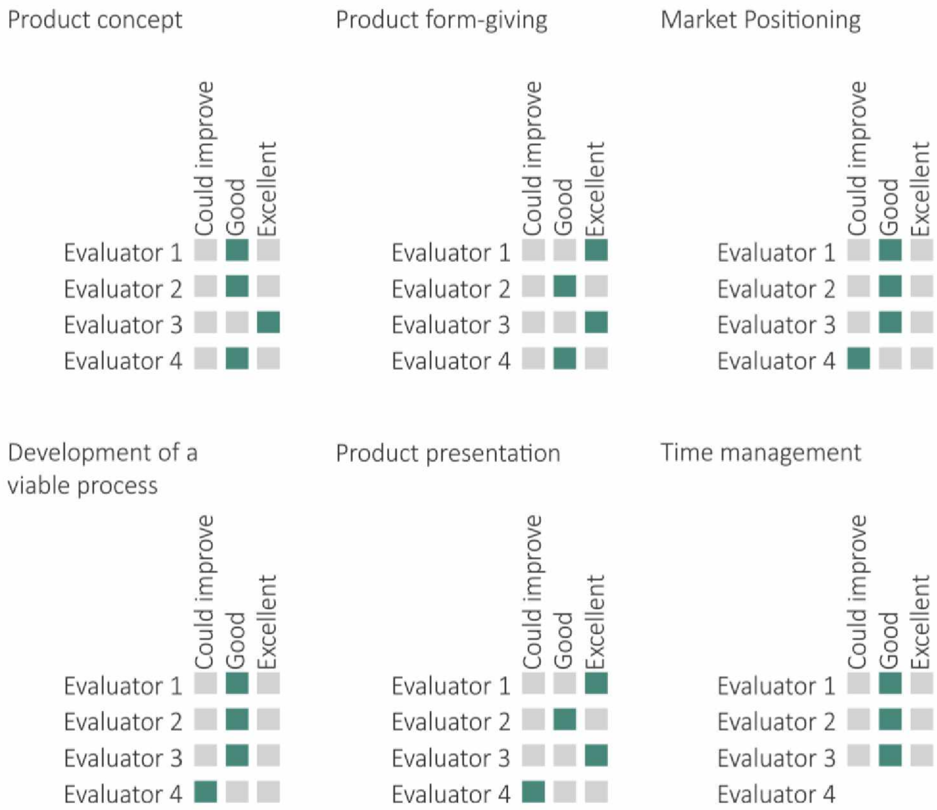
Figure 57 shows the renderings for the designs and the prototype production.

Figure 57 – Filó rendering and prototype production

Source: elaborated by the students (2022)

Figure 58 shows the ratings for the project, mainly evaluated as “good”:

Figure 58 – Evaluation of the Filó project



Source: Elaborated by the author (2022)

Mima – Students A11, A19, A17 and A28

Mima is a puzzle with a fairy-tale-like theme for children between the ages of 3 and 4 years. The students wrote for the design vision: “Thinking about the Cosmos collection (figure 1) [not included here, but are a set of decorative stars and moon for children’s bedrooms, painted in fluorescent natural colors], which was identified while researching products made out of mycelium, the team's intention is to create pieces that fit together, forming a puzzle. The collection emerges as an inspiration as its 10 pieces, aimed at the children's market, are pigmented through natural pigments, being able to shine with the incidence of light. The pieces are entirely made of mycelium grown in molds, being colored by pigments extracted from plants and with natural shellac mixed with phosphorescent powder. This way, the intention is to create colorful pieces, which still require tests and further research on methods of pigmenting the mycelium. (figure 2) [not included here], or even the creation of pieces with different formats (figure 3) [not included here]. The pieces will go through tests to be made either in molds or cut into the desired shape while the mycelium is still wet” (by the students, 2022, our translation).

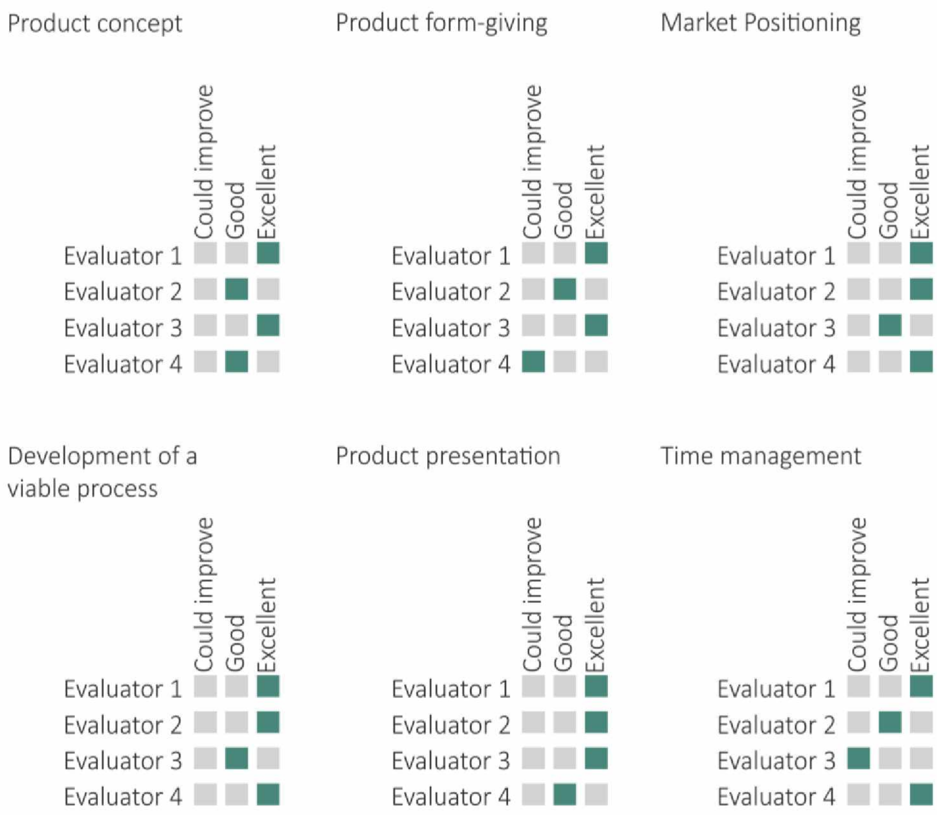
In their perceptual positioning map, they chose a “low number of pieces” and a “not too a low of a price” as a marketing strategy. The final product marketing price would be between 100,00 and 88,80 reais. A highlight of the project was the description of the product’s target audience. Figure 59 presents renderings for the design and the prototype development.

Figure 59 – Mima rendering and prototype production

Source: elaborated by the students (2022)

Figure 60 presents the evaluation of the Mima project, which received mainly "excellent" ratings:

Figure 60 – Evaluation of the Mima project



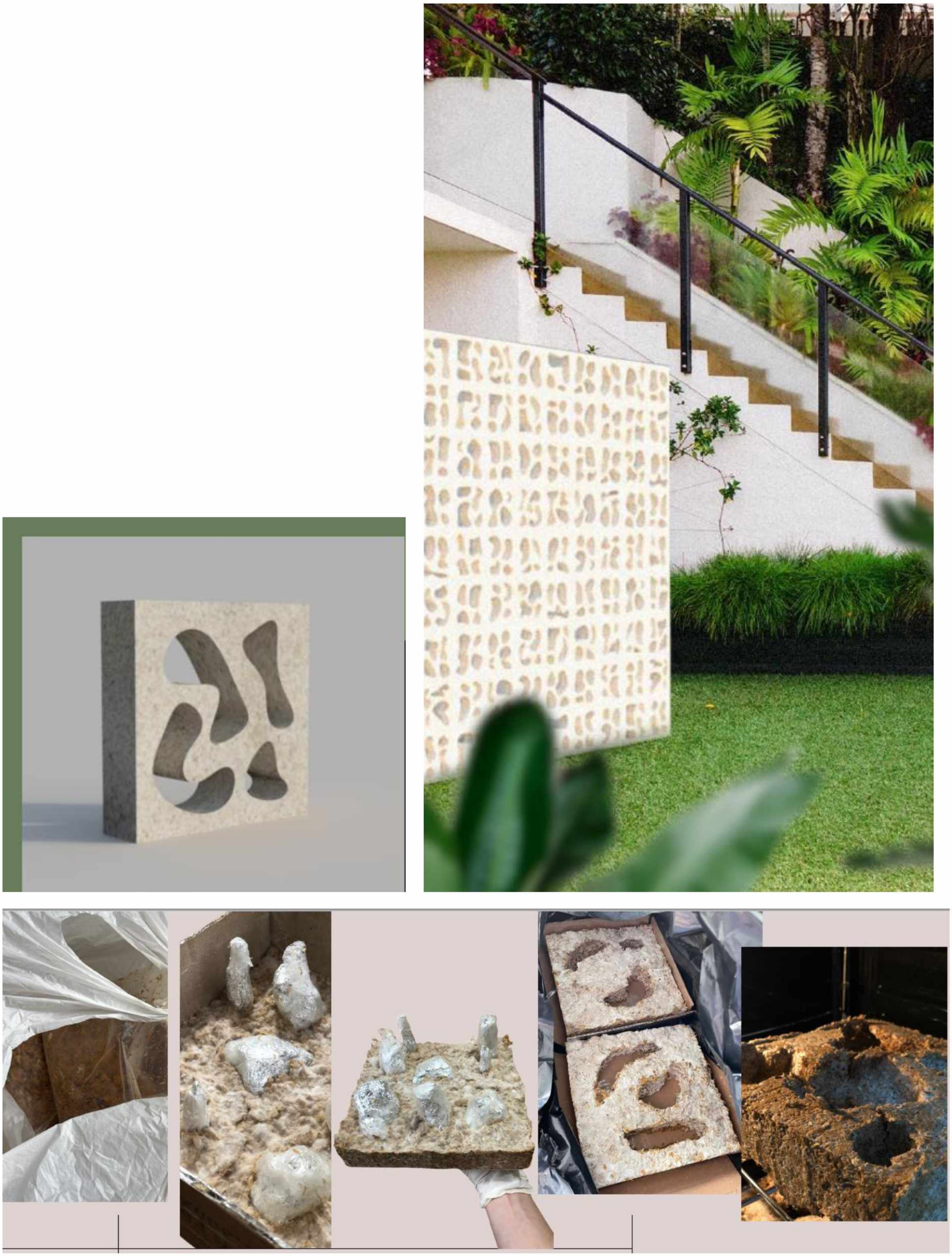
Source: Elaborated by the author (2022)

Cobogó Bió – A7, A8, A29 and A31

Cobogó Bió is a hollow construction element, traditional in Brazilian architecture, used to divide rooms allowing air and light to come through. The students' vision for the product was: "Use biomimetic design as a design premise. Biomimetic design understands form as a result of the elements of nature. In this way, a structure must be developed based on this inspiration; a pattern that generates a product capable of symbolizing this process" (by the students, 2022, our translation).

The perceptual positioning for the market was defined as "classic" and "contemporary", priced at 250 reais, to be sold in sets of 10 pieces. A highlight of the project was the competitor research and time management. Figure 61 presents the project's renderings and prototyping.

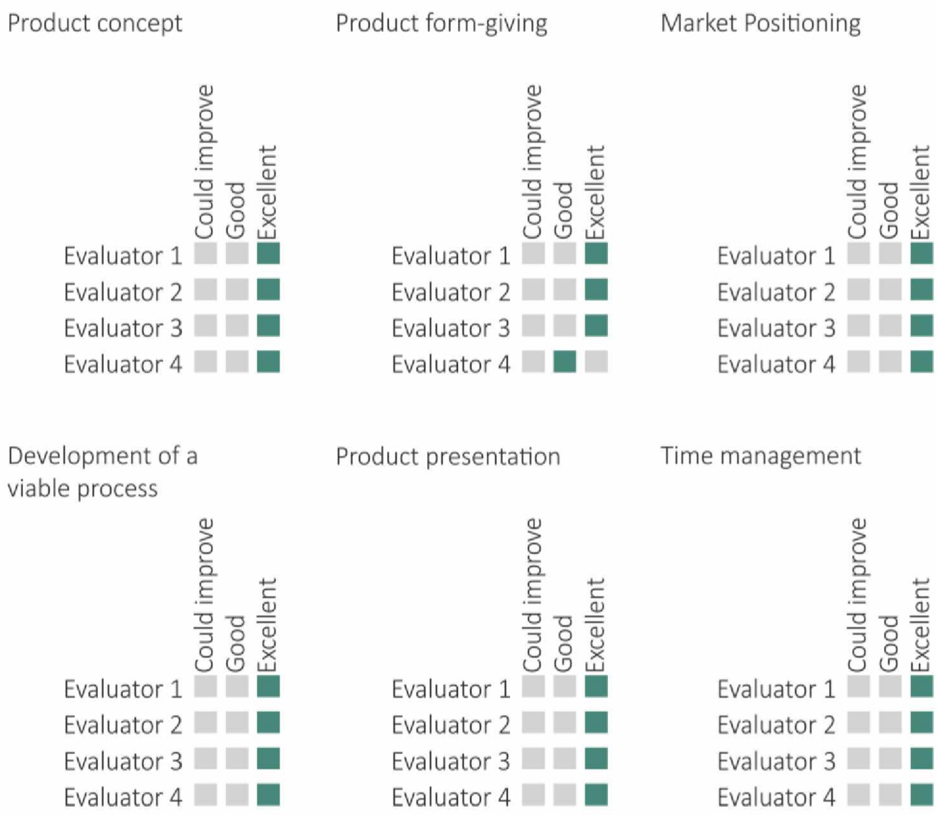
Figure 61 – Cobogó Bió rendering and prototype production



Source: elaborated by the students (2022)

Figure 62 shows the ratings for the project, which was mainly evaluated as "excellent".

Figure 62 – Evaluation of the Cobogó Bió project



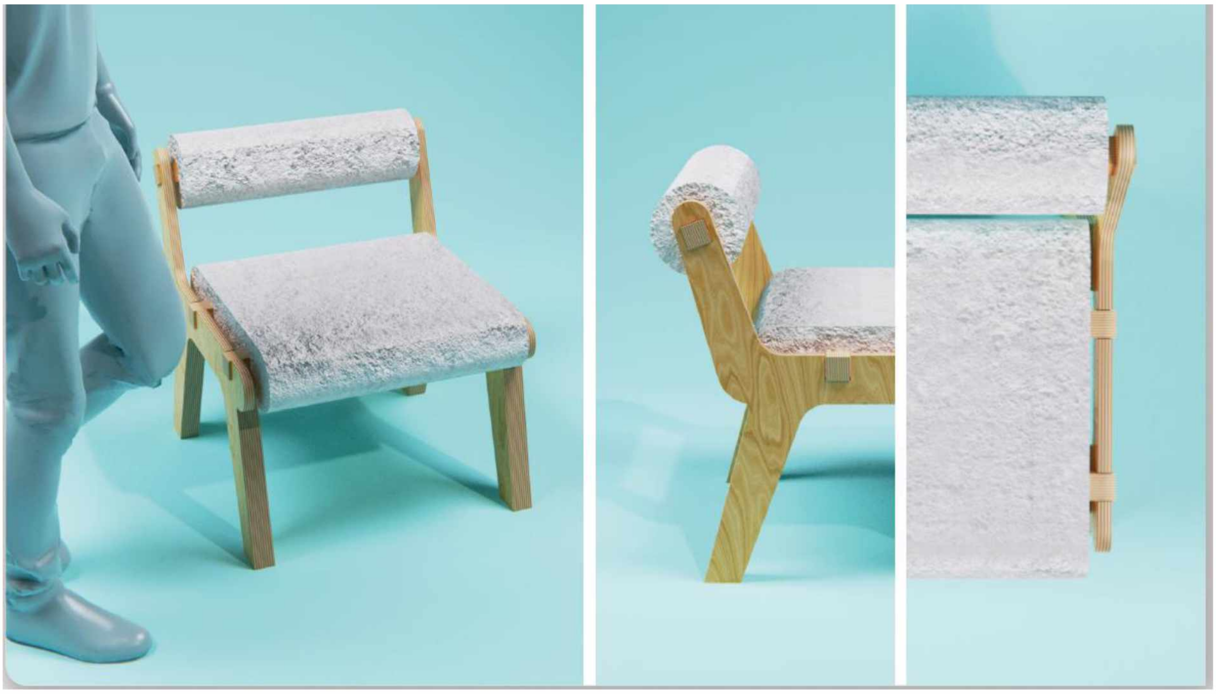
Source: Elaborated by the author (2022)

Hongo – Students A9, A16, A26 and A23

Hongo is a chair: "For the development of this project, we were inspired by some works that involve the creation of furniture pieces using mycelium, such as the one from the Philadelphia students Merjan Tara Sisman and Brian Mcclellan, whose research is called 'the living room project', which consists in an exploration of making objects with living materials. One of the processes presented in this study that generated interest and that will be applied in the development of the product, is the development of a wooden structure for support and application of mycelium in parts of a chair, in this case, the seat and backrest." (by the students, 2022, our translation).

The project was positioned in a perceptual map between the concepts of "Minimalist" and "Fewer materials". The estimated price for the product was 2.994 reais. Highlights of the Hongo project are the marketing positioning and the technical detailing of the chair. Figure 63 presents the renderings for the design.

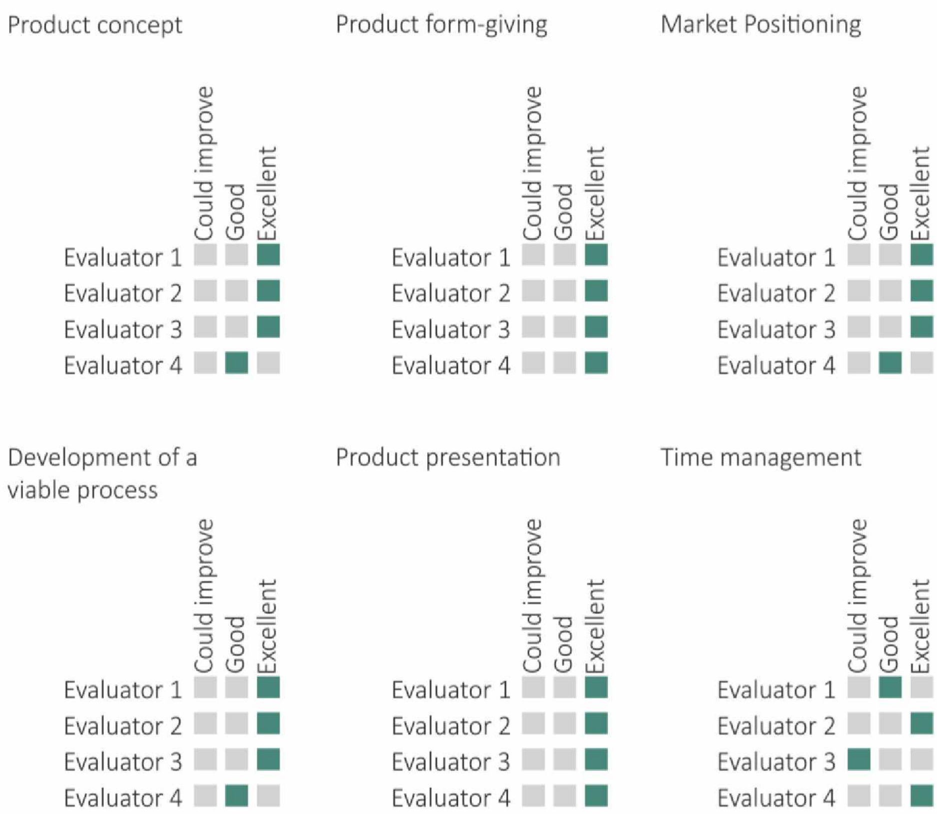
Figure 63 – Hongo rendering



Source: elaborated by the students (2022)

Figure 64 shows the ratings for the project, mainly evaluated as "excellent".

Figure 64 – Evaluation of the Hongo project



Source: Elaborated by the author (2022)

APPENDIX 8 – BACKGROUND FOR THE FRAMEWORK FOR BUILDING BIODESIGN PROCESS MODELS

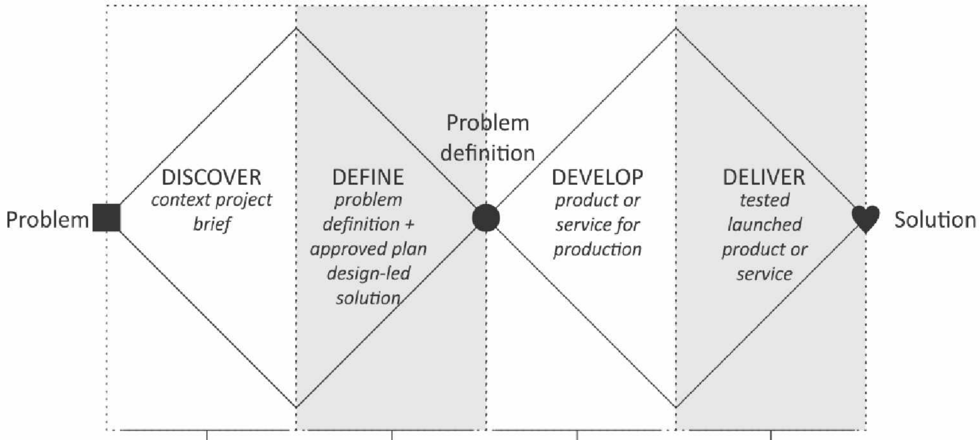
In 2007, the Design Council published a desk research report and a detailed study on the design process (DESIGN COUNCIL, 2007a; DESIGN COUNCIL, 2007b). They reviewed the literature from a historical perspective and performed in-depth interviews with eleven world-leading companies. The study used a design process model as a framework, which was also previously mapped by the Design Council: the Double Diamond - and “aimed to draw out some of the key features that define the state-of-the-art in modern design practice” (DESIGN COUNCIL, 2007a, p.1).

The first phase of the Double Diamond would be the (1) “Discovery” phase, which refers to the project’s starting point. It is the moment where divergent thoughts and perspectives would be desirable. Designers outline hypotheses, the problem, and “the playing field for design” (DESIGN COUNCIL, 2007a, p.9). According to the Design Council, it includes Market Research, User Research, Managing Information, and Design Research Groups. The second phase would be (2) “Define”, where business needs are interpreted and aligned according to findings from “Discovery”. Here, deep analysis takes place, and risks are scrutinized: “strategic dialogue takes place upfront, and potential bottlenecks, opportunities and no-go areas are defined ahead of the concept approval” (DESIGN COUNCIL, 2007a, p.14). Some solutions to the problem are already considered and even prototyped, the project develops safely as far as possible seeking predictability and impact in time and resources. According to the Design Council, activities would include: Project development, Project management, and Project sign-off. The third phase is (3) “Develop”, when “design-led solutions are developed, iterated and tested within the company” (DESIGN COUNCIL, 2007, p. 7). One or more concepts that were proposed in the previous phase would be now refined to be produced. Key activities are described as: Multi-disciplinary working, Visual management, Development methods, and Testing. This might be a sensitive part of the design process because change and bottlenecks are a possibility:

> Very often, insights from development rounds produce changes in product specifications. As development is often the most lengthy part of the design process, external factors can change too, with shifts in the market or competitor activities requiring late changes in requirements to be met (DESIGN COUNCIL, 2007a, p.22).

Finally in the last phase, (4) “Deliver”, the product is launched. Activities in this stage are mainly: final testing, approval and launch; and targets, evaluation and feedback loops. Teams assess the design process and learn lessons from the development case for future reference. Additionally, it is desirable to monitor business indicators to account for design credibility and contribution (DESIGN COUNCIL, 2007a). Figure 65 gives an overview of the Double Diamond model and lists the main activities for all phases in detail.

Figure 65 – Design Councils Double Diamond



Market research
identification of market gaps, improvement and innovation opportunities
- company related perceptions tracking (brand, products and services);
- competitor analysis;
- strategic analysis;
- future trends research (con-sumer, social, economic and environmental);

User research
prioritized in most interviewed companies - identification of products and services access, areas of improvement and innovation opportunities
- customer satisfaction and trends research;
- qualitative research (focus-groups, in-depth interviews, immersion experiences);
- storyboarding, scenario-building, multimedia prototypes and other tools (such as eye-tracking technology for testing user interaction with software)

Information management
design process as a framework for information flow and interaction across teams planning and management
- early strategic target setting for product and service development coordination;
- a formalized company's design process as a roadmap;

Designing research groups
incorporation of the design research process alongside the design process itself,
- creation (or commissioning) of design research teams;

Project development
initial development of project ideas and components
- team briefing and contextualization;
- project scope alignment (brand, business rationale and feasibility awareness - materials, logistics, time to market, sales goals, sustainability issues);
- proposition and evaluation of initial ideas (role-play, paper prototyping, day-in-the-life scenarios, sketching, colour, styles and trends consideration, project team scrums, selection processes, brainstorms);
- review and research;

Project management
project management tools (for predictability, risk assessment; team communication, decision making support)
- collaborative, visual and centralized management tools;
- AGILE approaches;

Project sign-off
- presentation of a well-argued business case alongside a proposed design approach (in some cases including prototypes)

Multidisciplinary work
- establishment of direct communication channels (speed up problem solving and avoid bottlenecks);
- close collaboration with manufacturing, engineering, consultancy teams and external suppliers and manufacturers;

Visual management
- project management on a visual nature;
- iterations of sketches, prototypes, testing, scenarios;
- workflow graphics;
- tracking of project deliverables, developments, timings and internal or external dependencies;

Development methods
prototyping and iteration
- sketches and renderings, detailed 3D computer models (virtual prototyping methods), physical models;
- analysis methods, (such as Failure Mode and Effects Analysis - FMEA);

Testing
major part of the Development stage
-testing principles and protocols (such as Six Sigma);
- design check to consistency with user needs and corporate strategy,
- product capabilities check;
- market research methods (focus group, field and in situ consumer observation, simulations);

Final tests, approval and launch
- final constraints or problems before manufacturing;
- check against standards and regulations;
- damage testing and compatibility testing;
- liaison with teams in areas such as marketing, communications, packaging and brand;
-production of photographic instructions and directions;

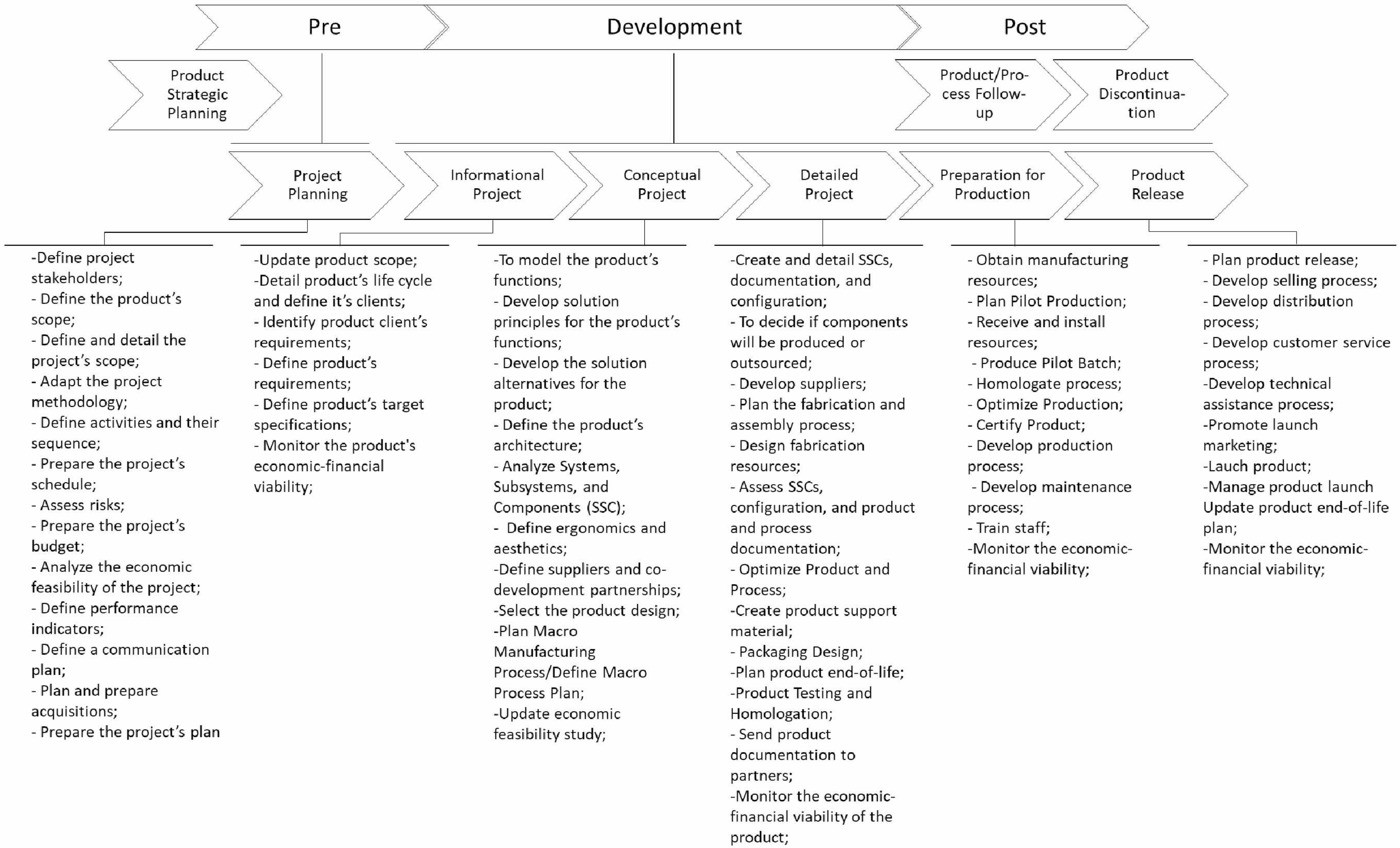
Targets, evaluation and feedback loops
-business performance metrics (sales, market share);
-customer satisfaction tracking surveys;
-data on the sales of spare parts or logged in-service failures;
-method banks, case study libraries;

Source: Illustrated by the author (2021), based on Design Council (2007, pp.6-7)

The second study used to formulate the design process analysis framework is Rozenfeld et al.'s (2006) **Product Development Process (PDP)** from the book: "*Gestão de desenvolvimento de produtos: uma referência para a melhoria do processo*" (Managing product development: a reference for process improvement - our translation). It is the model used to structure the deliverables in students' graduation projects at the Federal University of Paraná's Product Design course. As this is the institution that offers the context for this Ph.D. research project, the PDP is chosen to form the framework along the Design Council's Double Diamond and the Mosaic Method. Besides the book, the available information on Rozenfeld's group's updated website is also used here (PDP, 2023).

The PDP is organized in 3 macro-phases (see Figure 66): Pre-development, Development, and Post Development. In this study, the focus is on the Development macro-phase, in addition to one phase from the Pre-Development: (1) Project Planning. The Project Planning phase's objective is to perform the macro-planning of the development. In Project Planning an effort is made to identify all activities, resources, and how to best integrate them so that the project strives with a minimum of errors. The result is the product development plan, which comprises information relevant to the project execution (PDPnet, 2023). After the Project Planning, the next phase according to Rozenfeld et al. (2006) is the (2) Informational Project. The objective of this phase is, based on the information collected in the Planning and other sources, to develop a set of information, as complete as possible, called the "product's target specifications" (PDPnet, 2023). The (3) Conceptual Project activities are related to the search, creation, representation, and selection of solutions for the design problem (PDPnet, 2023). In the (4) Detailed Project the goal is to develop and finalize all product specifications, so the product can go to manufacturing. The (5) Preparation for Production phase aims to prepare for the release of the product in the market. It involves the production of the pilot batch and the definition of the production and maintenance processes. It also deals with supply chain activities (PDPnet, 2023). Finally, the (6) Product Release aims to release the product in the market, it involves the design of the sales and distribution processes, customer service and technical assistance, and the marketing campaigns, i.e. the supply chain activities related to getting the product to the market (PDPnet, 2023). Figure 66 shows the PDP model overview and the main design tasks for each phase.

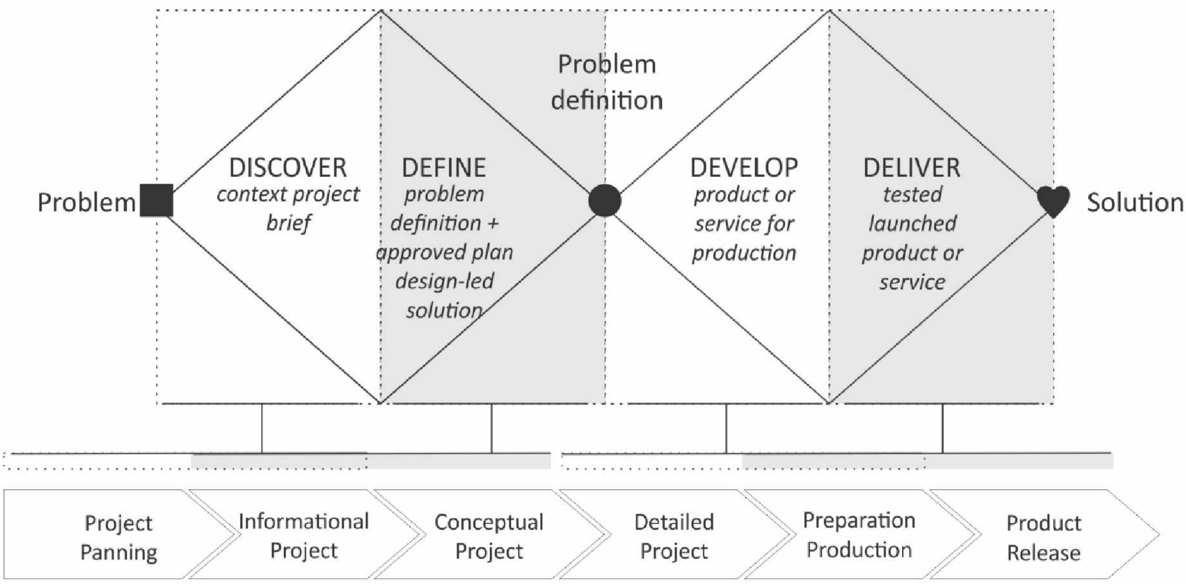
Figure 66 – Rozenfeld's et al. Product Development Process reference model



Source: Illustrated by the author (2023), based on PDPnet (2023

Figure 67 presents how the Design Council phases and the PDP phases relate to each other.

Figure 67 – Rozenfeld's et al. Product Development Process reference model and Design Council's Double Diamond



Source: Illustrated by the author (2021), based on Design Council (2007a) and Rozenfeld et al. (2006)

To compile design process dynamics from the interviews, an adaptation of Kim and Lee's (2017) Mosaic method is used. The authors categorize this method as a grounded theory approach. In their original study, they interview designers and engineers in consumer product companies. The aim is to define representative models of typical types of product design collaborative processes. **This approach acknowledges the multiple possible design processes, and it proposes an assembled representation**. Kim and Lee (2017) seek (a) to look into the collaborative design process **in context** and (b) to determine "different types of processes used for different purposes under different conditions" (KIM; LEE, 2017, p. 227). The Mosaic method is composed of five main phases. To begin with, Kim and Lee perform (1) individual in-depth interviews with each designer and engineer of the team, inquiring about their design process. The interview process is divided into four themes: (a) personal information; (b) design process; (c) role and expertise; and (d) interaction (KIM; LEE, 2017, p. 231). Sometimes, interviewees produce drawings. For coding the interview information the authors predefined themes, to which they establish categories linking the transcripted data. They have an intricate system, coding data in: (a) task; (b) event; (c) information flow and (d) interaction. Following the coding process, (2) a representation of each interview is drawn, placing "**process elements**" chronologically in a flowchart. "Stages" are then composed of: (a) one input, (b) one task, one (d) event, and one (e) output.'Kim and Lee (2017) also compare their representations to the company's standard design process official documentation. The third step is to develop (3) a combined representation of each design team. Those are simplified in "process chunks", to allow better comparability. The process chunks are more "general" in relation to the process elements, comprising more than one stage. They describe a job as having an "irreversible tendency". Feedback and iterations may occur across stages inside the chunk (KIM; LEE, 2017). Process chunks are then (4) simplified as "**process models**" and (5) categorized in a **typology**. The models are also sent to the interviewees to discuss their interpretation of the analysis and changes are made when necessary. The typologies' names refer to the aforementioned project types: inside-out or outside-in-led designs. Finally, some application recommendations for the process models are given. As later described in the results, after the pilot interview, it was understood that it would be difficult to work with the intricate details in the identification of the difference between a process element, a task, and a process chunk. This differenciation could fatigue the interviewees and make the in-detail interview too long. Hence, after the interviews are described, information is crossed over with the drawings of the design processes provided by the interviewees. All of the tasks, stages, and chunks are considered general process elements and are represented in the models with color differentiation in small little squares according to the amount of time they took to be completed. This allows to maintain the design process models as loyal to the interviewee's vision as possible.

APPENDIX 9 – PAPER FORMAL EDUCATION IN INTERSPECIES DESIGN COLLABORATION (BIODESIGN)*

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O ensino formal da colaboração em design interespécies (biodesign)

Formal education in interspecies design collaboration (biodesign)

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Sustentabilidade geral/ODS (Objetivos para o Desenvolvimento Sustentável)

Resumo

A comunidade de biodesign (colaborações interespécies em design) parece estar caminhando para uma sólida auto-organização e formalização. Alguns autores especulam que a aproximação com a biologia poderia marcar a prática do design do século 21. Parece relevante entender como o ensino e a aprendizagem acontecem no biodesign para desenvolver como poderiam ser melhor introduzidos nos currículos de design. Parece que ainda não foi feita uma análise da educação formal em biodesign. Para atender a esta lacuna de pesquisa, este trabalho visa compreender o cenário da educação formal em biodesign através de uma análise de alguns dos principais cursos e programas. A estratégia metodológica é uma revisão sistemática e narrativa por meio de um buscador popular. Foram analisados 16 resultados: 1 masterclass para profissionais, 8 disciplinas, 1 curso de graduação (Major), 4 programas de mestrado e 2 de doutorado.

Palavras-chave: Biodesign; Design Interespécies; Educação Formal

Abstract

The community of biodesign (interspecies design collaborations) seems to be heading toward solid self-organization and formalization. Some authors speculate that the approximation to biology could mark the design practice of the 21st century. It seems relevant to understand how teaching and learning are happening in biodesign to develop how it could be further introduced in design curricula. It doesn't seem that an analysis of formal education was made yet. To address this research gap, this paper aims to understand the formal education scene in biodesign through an analysis of some of the main biodesign courses and programs. The methodological strategy is a systematic and a narrative review through a popular search engine. 16 results were analyzed: 1 Masterclass for Professionals, 8 courses, 1 undergraduate course (Major), 4 master's, and 2 Ph.D. programs.

Keywords: *Biodesign; Interspecies Design; Formal Education*

1. Introduction

The community of biodesign seems to be heading toward solid self-organization and formalization. The consistency of specific competitions suggests that biodesign is not an ephemeral trend: like the "Bio Art & Design Award" (BAD, 2021), since 2011, and the "Biodesign Challenge" itself, since 2016. The subject also features events, like the annual Biofabricate summits (BIOFABRICATE, 2021), the "Design with the Living" annual Symposium (DESIGN MUSEUM, 2020), and "Still Alive" (STILL ALIVE, 2020). These events bring together researchers from around the world.

The term biodesign has many interpretations, in this paper, Dade-Robertson's definition is the reference: "[...] design and design research which use living systems as part of their production and operation" (2021, series introduction note) – in other words, biodesign implies in interspecies design collaborations. Examples of the biodesign practice include works with different species, from bacteria to animals. For instance, the company Fullgrown shapes living trees into furniture through horticultural techniques (FULLGROWN, 2021); Modern Synthesis weaves bacteria into shoes (MODERN SYNTHESIS, 2020); the Blast Studio develops 3D printed mycelium modules to compose objects such as lamps and columns (BLAST STUDIO, 2020); The Reef Design Lab develops 3D printed calcium carbonate structures to be collaboratively fulfilled with corals (REEF DESIGN LAB, 2021). Some of these examples are illustrated in Figure 1.

Figure 1 - Biodesign examples.

Source: From left to right: Fullgrown's chair production (MATERIAL DISTRICT, 2018). Modern Synthesis' microbial woven shoe (MODERN SYNTHESIS, 2020) and Blast Studio's 3D printed mycelium lamp shade (BLAST STUDIO, 2020)

Some authors speculate that the approximation to biology could mark the design practice of the 21st century: "Building with bacteria and other organisms is simultaneously becoming a technological possibility and a necessity" (MYERS, 2018, p.16). Collet writes that "the beginning of the twenty-first century marks a strong shift towards the amalgamation of the binary code (1s and 0s) with biological systems" (2020, p.1). She sees a shift in the role of design "from working with inanimate matter such as plastic and metals to making with animate living entities such as mycelium, yeast, and bacteria" (COLLET, 2020, p.1).

Designing with the living is reportedly different from what designers are used to. Antonelli writes that "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 says that "You can't master life in the way a painter masters oils or a joiner masters wood" (2021a, p. 95). To Collet (2020), growing would now be part of the design process, which impacts form, structure, aesthetics, and material specification. The creating and controlling, she argues, brings to light new competencies to the designer besides the traditional methods they would be used to. Camere and Karana (2018) refer to these new skills and competencies as the "new designerly sensibilities".

It seems relevant to understand how teaching and learning are happening in biodesign to develop how it could be further introduced in design curricula. It doesn't seem that an analysis of formal education was made yet. To address this research gap, this paper aims to understand the traditional education scene in biodesign through an analysis of some of the main biodesign courses and programs. In the following sections, the methodological strategy for finding and analyzing the courses and programs is presented; following the results and discussion; finally, conclusions are drawn with recommendations for future studies.

One last consideration to be acknowledged before beginning is that this research intention still lies in an anthropocentric perspective of science because it still thinks in means to operationalize collaboration with living organisms in terms of a useful resource. But the hope is that it leads to a respectful conscience and way of treating living organisms, and towards a more ecocentric attitude of design (MELKOZERNOV; SORENSEN, 2020). This is also why the term collaboration is used to describe the relationship of the designer with other living organisms.

1. Methodological Strategy

The systematic review is adapted from Conforto, Amaral, and Silva's (2011) roadmap. The selected search engine is Google, using the search strings: "biodesign" AND "course"; "biodesign" AND "master's" OR "Ph.D." OR "graduation"; "biodesign" AND "program" OR "programme".

The filter application follows an open reading strategy, exclusion criteria are:

(1) courses that are not provided by universities

(2) courses in which the scope are not designers

(3) term disambiguation – when the term biodesign is not related to design and only related to medical and health sciences. When it refers only to biomimicry, not to biodesign as described by Dade-Robertson (2021);

To prevent some biases, such as search strings, a narrative review was also necessary (FERRARI, 2015) and references found in the literature were added.

In the analysis process, available data were organized into three categories when the information was available: (1) Title, University, Course Load; (2) Infrastructure; (3) Course overview. The process involved reading each course material and summarizing it.

2. Results and Discussion
3.

After the filter application, the systematic review retrieved 14 results. The Biostudio project summarized some of the opportunities to study biodesign (BIOSTUDIO, 2021) – through this reference, one more result was added. Finally, a paper was found about a biodesign course at the Faculty of Fine Arts and Design of the University of Economics of Izmir. The analysis comprised 1 Masterclass for Professionals, 8 courses, 1 undergraduate course (Major), 4 master's, and 2 Ph.D. programs. Table 1 presents information for each of these initiatives:

Table 1: Masterclasses, courses, undergraduate courses, masters and Ph.D. programs

1	**Title:** Biological Design (course) - University of Pennsylvania **Course load:** not informed **Infrastructure:** not informed **Course overview:** The course assumes the dynamics of a studio. According to Upenn (2023), it is a research-based course that "introduces new materials, fabrication, and prototyping techniques to develop a series of design proposals in response to the theme: Biological Design". Life sciences and biotechnologies are introduced to designers, artists, and non-specialists. (UPENN, 2023)
2	**Title:** Biomaterials: Designing with Living Systems (course) - Faculty of Fine Arts and Design of the University of Economics of Izmir **Course load:** not informed **Infrastructure:** not informed **Course overview:** [...] Pedagogical objectives are: "to reinforce basic design principles through a new media and to broaden the students' understanding of design as a cross-disciplinary problem-solving process" (PINTO; PUGLIESE, 2017, p.1). Activities of the course comprise: "observation, tinkering, playing, gathering, sketching, experimenting and predicting" (PINTO; PUGLIESE, 2017, p.2). Students work together on projects around a specified organism, like silkworms. The course is organized into two main modules: one theoretical and one "application unit". The theoretical module presents a case study analysis and introduces to the basics of "morphological, physiological, anatomic, behavioral, origin, and distributional, aspects of many biological actuators and in particular silkworms" (PINTO; PUGLIESE, 2017, p.4-5). In the applied module students developed their own projects around a design hypothesis and scenario simulation. Students were asked to make records of their progress and the development of the other organism in the project (PINTO; PUGLIESE, 2017).
3	**Title:** BioDesign Fundamentals course – The University of Sidney

	Course load: 6 credit points **Infrastructure:** not informed **Course overview:** According to the course description, it presents basic concepts of designing with science and reinforces the participant's own domain expertise, augmenting the participant's existing skills with new approaches to problem-solving. The unit introduces "prototyping for science and biology, evaluating ethical implications of designing with life, communicating scientific processes to justify biodesign choices" (THE UNIVERSITY OF SIDNEY, 2023), and shows the participant to support peers with their own expertise. Learning objectives are related to: ethical concerns; prototyping in a biodesign context; interdisciplinary thinking; developing the ability to explain scientific concepts "using abstracted models to a broad audience"; supporting peers in the development of new skills; and "understand the theory, methods, and technology that underpin key approaches to biodesign" (THE UNIVERSITY OF SIDNEY, 2023).
4	**Title:** IDE Design Master Class for Professionals – Biodesign - TUDelft- **Course load:** 2 days, paid course **Infrastructure:** not informed **Course overview:** The course introduces the participants to the "world of living organisms, to fundamental biodesign theories, tools, and methods to understand and design with living organisms" (TUDELFT, 2023) – it is oriented to a "cleaner production and unique experiences in everyday products" (TUDELFT, 2023). Learning objectives concern: theory and principles of biodesign; "get a feeling for bio lab tools and machines, basic bio lab technical and research skills to grow, maintain, and observe living organisms"; hands-on experiences; and "gain competence in envisioning future applications for living materials" (TUDELFT, 2023).
5	**Title:** (1) Biodesign theory and practice: biodesign challenge part I (course) and (2) biodesign experimentation and prototyping: biodesign challenge part II (course) - University of California, Davis **Course load:** 3 hours (part I) +3 hours (part II) **Infrastructure:** not informed **Course overview:** These courses prepare the participants to take part in the Biodesign Challenge (BIODESIGN CHALLENGE, 2023). Students must enroll separately in each part. Part I gives the participants an overview of biodesign foundational principles, presenting biodesign examples in many segments. Later on, it develops participants' "team-based experience in biodesign intervention; first steps in a mini-entrepreneurial start-up experience" (UNIVERSITY OF CALIFORNIA, DAVIS, 2023). Part II is the continuation of the team's work, focusing on prototyping.
6	**Title**: The Biodesign Challenge (course) – University of Cincinnati **Course load:** not informed **Infrastructure:** not informed **Course overview:** The course aims to prepare students to participate in the Biodesign Challenge. Participants work in interdisciplinary teams, with advice from experts to solve a specific problem. Focus lies on ideation and prototyping (UNIVERSITY OF CINCINNATI, 2023).
7	**Title:** Aesthetic Crossovers of Art and Science and Art and Life Manipulation (courses) – The University of Western Australia **Course load:** not informed **Infrastructure:** not informed **Course overview:** There are two elective courses, the first one, called Aesthetic Crossovers of Art and Science, focuses on "A practical and theoretical investigation, through critical engagement of the nexus and differences of the art and science cultures through the use of the technologies of life science/biotechnology as an art-form" (UWA, 2022). The second course, called Art and Life Manipulation, aims at introducing biological lab "practices and techniques dealing with the manipulation of living biological systems within the context of contemporary arts practices" (UWA, 2022).
8	**Title**: Biological Design Major – The University of Sidney **Course load:** not informed **Infrastructure:** not informed

	Course overview: This program brings together design principles, along with biomedical science and engineering to create innovative solutions for human and planet health (THE UNIVERSITY OF SIDNEY, 2022). Students learn about ethical implications, prototyping for Science and biology, communicating scientific processes, and supporting peers with their own expertise. There are also interdisciplinary projects with industry partners including one aiming at the Biodesign Challenge (THE UNIVERSITY OF SIDNEY, 2022). The courses in the program are (some of them have an advanced version): - Animal behavior; BioDesign Fundamentals; BioDesign Studio; Biology of Insects; Biomedical Design and Technology; Biomedical Engineering 1B; Botany; Cell Biology; Co-Design and Participatory Approaches; Design Thinking; Design for Wellbeing; From Molecules to Ecosystems; Fundamentals of Human Anatomy; Fundamentals of Visual Design; Global Challenges: Food, Water; Human Biology; Industry and Community; Introduction to Interface Design; Key Concepts in Physiology; Life and Evolution; Principles of Design; Reproduction, Development, and Disease; Responsible Design for Innovation; Science Interdisciplinary Project; Systems Physiology; Terrestrial Plant Ecosystem Management; Zoology (THE UNIVERSITY OF SIDNEY, 2022).
9	**Title:** Master of Biological Arts – The University of Western Australia **Course load:** not informed **Course overview:** The program emphasizes on developing "critical thought, discussing ethical and cultural issues, and encouraging cross-disciplinary experimentation in art and science" (UWA, 2022). The target audience of the master's is art practitioners, scientists, and humanities scholars who wish to engage with creative bioresearch. Students must take art and science credits – with a balance of disciplines (UWA, 2022).
10	**Title:** Master of Arts Biodesign - University of the Arts London **Course load:** 2 years, 30 hours per week (180 credits) **Infrastructure:** Grow-Lab (Containment Level 1 biology laboratory); Biologist in the teaching team; International network of the Design & Living Systems Lab; Knowledge exchange with industry partners. (UAL, 2022). **Course overview:** The curriculum is research-driven, with an emphasis on ethical concerns and learning by making – students develop a personal research agenda. Learning objectives concern: understanding critical context challenges for design in the 21st century "social, political, economic, ethical and sustainable issues" (UAL, 2022); bio-informed design strategies and whole system thinking; biomimicry principles in design; biological sciences and biofabrication tools and methods; sophisticated lab-based biodesign practice; "to explore and integrate biocomputation tools into design practice" (UAL, 2022, p.5); to develop biodesign portfolio of work. The program is divided into three units: (1) Seed; (2) Grow; (3) Harvest. The first unit forms the theoretical basis and students develop a series of small projects, it concludes with the submission of a biodesign portfolio [... and an] oral and visual presentation" (UAL, 2022, p. 8). The second unit focuses on a personal project to apply the different biodesign competencies. The third unit is dedicated to "creative production and communication of the final MA project" (UAL, 2022).
11	**Title:** Master of Architecture Bio-Integrated Design (Bio-ID) – University College London **Course load:** 2 years (300 credits) **Infrastructure:** BiotA Lab (Biotechnology and Architecture Lab). Taught jointly by UCL's "The Bartlett School of Architecture" and "Biochemical Engineering Department". **Course overview:** The course aims to "[...] integrate biotechnology, advanced computation, and fabrication to create a radically new and sustainable built environment" (UCL, 2022). Students work simultaneously in a scientific laboratory, in a design studio, and at a fabrication workshop. Participants engage in short projects in teams and also in a speculative design project (thesis). The final module aims at research career preparation. Course modules consist of: - Introduction to Scientific Methods, Laboratory and Environmental Practices; Computational Skills; Literature Review; Preliminary Design; Year 1 Design Project and Fabrication; Year 1 Thesis Report; Design Specialisation and Interdisciplinary Context; Comprehensive Project Thesis.

Table continues next page

12	**Title:** Biological Design, MS – Arizona State University **Course load:** 30 credit hours and a thesis, or 30 credit hours including the required applied project course **Infrastructure:** not informed **Course overview:** The program emphasizes a continuum between technology and biology. Students have to "take one program core course (Principles of Biological Design), one course from a suite of biotechnology courses, and one from a suite of statistics courses" (ASU, 2022). In this program "students read literature; identify critical problems related to energy, environment, human health, sustainability, and security; and develop solutions to these problems using a synergy of technological and biological solutions, either in teams (course projects) or individually (thesis or applied project)" (ASU, 2022). Courses are: - Research Methods in Biological Design (mandatory); Topic: Six Sigma Methodology/Engineering Experimentation (statistics); Design Engineering Experiments (statistics); Regression Analysis (statistics); Mathematical Statistics (statistics); Topic: Bioenergy and Microbial Biotechnology (biotechnology); Topic: Cellular and System Modeling (biotechnology); Topic: Chimeras and Recombinant Organisms in Medicine (biotechnology); Advanced Environmental Biotechnology (biotechnology); Environmental Microbiology (biotechnology); Topic: Bio-inspired Design (biotechnology); Microbial Bioprocess Engineering (biotechnology); Topic: Nanobiotechnology (biotechnology); Topic: Synthetic Biology and Metabolic Engineering (biotechnology); Seminar; Applied Project; Thesis.
13	**Title:** Biological Design Ph.D. – Arizona State University **Course load:** 84 credit hours Table continues next page **Infrastructure:** not informed **Course overview:** "The program is a joint effort by the College of Liberal Arts and Sciences, The Biodesign Institute, and the Ira A. Fulton Schools of Engineering" (ASU, 2022). Besides the credits, a qualifying exam, a comprehensive exam/proposal prospectus, and a dissertation are required. There is a system of research rotations, where students rotate between laboratories in order to define a potential advisor and research topic. After the first year, students decide on one of the three labs for their Ph.D. studies. Besides the credits of specialized coursework, "there is a recommendation to include courses with components in bioethics and grant writing" (ASU, 2022). Some of the courses offered: -Biological Design II (required); Biological Design Proseminar; Biological Design Seminar; Research; Lab Rotations; Dissertation; Patterns in Nature; Materials Synthesis; Structure and Properties of Materials; Materials and Civilization; Sensing the World (ASU, 2022).
14	**Title:** Biological Arts and Ph.D. – The University of Western Australia **Course load:** not informed **Infrastructure:** not informed **Course overview:** Not informed, a general statement is given: "Emphasis is placed on developing critical thought, discussing ethical and cultural issues, and encouraging cross-disciplinary experimentation in art and science" (UWA, 2022).

Source: Authors.

It is important to note that biodesign education happens in other educational constellations, such as the "Cluster of Excellence Matters of Activity" (MoA, 2023) and the "Hub for Biotechnology in the Built Environment" (HBBE, 2023). The cluster and the hub gather funding around common projects – where Ph.D. students and other researchers develop their projects associated with these initiatives. The cluster even has a Ph.D. program, but it is not exclusive to biodesign projects.

Course load varies between institutions. For example, the Master's in Biological Design, from Arizona State University requires 30 credit hours and a thesis, while the Master of

Architecture in Bio-Integrated Design (Bio-ID), from the University College London, requires the completion of 300 credits.

Infrastructure is not always informed, a highlight is the University of the Arts London, which offers a containment level 1 biology laboratory, a biologist in the teaching team, an international network, and knowledge exchange with industry partners. (UAL, 2022).

Regarding the course overview, five results emphasize laboratory work or introductions (TUDELFT, 2023; UWA, 2022; UAL, 2022; UCL, 2022; ASU, 2022). A highlight of this approach is given by Arizona State University (ASU, 2022), where students rotate between laboratories to define a research interest and an advisor. Ethical implications are a main topic in five of the results (THE UNIVERSITY OF SIDNEY, 2023; THE UNIVERSITY OF SIDNEY, 2022; UWA, 2022; ASU, 2022; UWA, 2022). Project/studio structures are adopted by 7 of the initiatives (UPENN, 2023, PINTO; PUGLIESE, 2017; ASU, 2022; THE UNIVERSITY OF SIDNEY, 2022; UNIVERSITY OF CINCINNATI, 2023; UNIVERSITY OF CALIFORNIA, DAVIS, 2023; ASU, 2022). Interdisciplinary experience is promised by 6 of the results (THE UNIVERSITY OF SIDNEY, 2023; THE UNIVERSITY OF SIDNEY, 2022; UWA, 2022; UCL, 2022; ASU, 2022; UAL, 2022). Prototyping is the focus of five of the courses/programs (UPENN, 2023; THE UNIVERSITY OF SIDNEY, 2023; UNIVERSITY OF CALIFORNIA, DAVIS, 2023; UNIVERSITY OF CINCINNATI, 2023; THE UNIVERSITY OF SIDNEY, 2022). Market-driven/application-driven solutions are the goal of TUDelft (2023) and the University of California, Davis (2023). The University of Sidney (2023) and the University of the Arts London (UAL, 2022) emphasize on the ability of the students to communicate their projects. Four of the initiatives were oriented or had activities oriented to the participation in the Biodesign Challenge (2023) (UNIVERSITY OF CALIFORNIA, DAVIS, 2023; UNIVERSITY OF CINCINNATI, 2023; THE UNIVERSITY OF SIDNEY, 2022). The Biodesign Challenge is an international competition sponsored by companies like Google, Science Sand Box, Ginkgo Bioworks, and others. It introduces students to the intersections of biotechnology, art, and design. Universities and high schools may register, gaining access to pedagogical resources and a mentor network.

In the next section, the final considerations are outlined, along with the recommendations for future research.

4. Final considerations

The biodesign community, which collaborates in interspecies designs, seems to be reaching a solid development. It seems relevant to understand how teaching and learning are happening in biodesign to develop how it could be further introduced in design curricula. It didn't seem that an analysis of formal biodesign education had been made yet. To address this research gap, this paper aimed to understand the formal education scene in biodesign through an analysis of some of the main biodesign courses and programs. The methodological strategy was a systematic and a narrative review through a popular search engine, Google. 16 results were analyzed: 1 Masterclass for Professionals, 8 courses, 1 undergraduate course (Major), 4 master's, and 2 Ph.D. programs.

It was found that biodesign education doesn`t happen only in biodesign formal programs – but also happens in other constellations, like the "Cluster of Excellence Matters of Activity" and the "Hub for Biotechnology in the Built Environment". The course load varies greatly between institutions. Infrastructure and resources are not widely informed, but some initiatives state that they offer laboratories. Course overview highlights are: laboratory work or introductions; ethical implications; project/studio structures; interdisciplinary experience; prototyping; focus on market-driven/application-driven solutions; the development of the ability of the students to communicate their projects; and activities oriented to the participation in the Biodesign Challenge.

For future studies, it seems interesting to interview the teachers and professors in these institutions and to look into other educational constellations, such as Matters of Activity, the Hub for Biotechnology in the Built Environment, and others.

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