Design with The Living: Learning to Work Together

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ABSTRACT

Designing with other living organisms (biodesign) is reportedly different from designing with traditional materials such as glass and wood. This paper aims to present the development and testing of a framework for teaching and learning the biodesign process in an undergraduate context with limited resources. Limited resources meaning the lack of a studio space and a laboratory. This seems to be a research gap in the literature review. The methodological strategy to achieve the framework is Design Science Research. The framework is organized in two context spaces: classroom and the student`s homes. Six are its elements: (1) Concepts, (2) Repertoire, (3) Project methodology, (4) Practice, (5) Management, and (6) Reflections. There are materialities to the framework, like a project journal and a grow-it-yourself kit – as well as activities, like brainwriting and tinkering. The framework was evaluated in an undergraduate Product Design program with no access to a laboratory and no proper studio space. Through triangulation, we found that 14 of the established learning objectives were considered as met and 7 were considered as partially met. We discuss the results with other biodesign practices in formal education. Future developments of the framework include creation of an elective introductory biodesign course.

Keywords: Biodesign, Interspecies Design, Undergraduate Education

INTRODUCTION

Dade-Robertson describes biodesign as: "[...] design and design research which use living systems as part of their production and operation" (2021, series introduction note). Designing with the living, or biodesigning, is reportedly different from what designers are used to (Camere & Karana, 2018). 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". Figure 1 presents an example of the practice, the chairs designed by Fullgrown (https://fullgrown.co.uk/). In this case, the trees are shaped into chairs while they grow, in other words, the designers negotiate the chair`s final form with the tree.

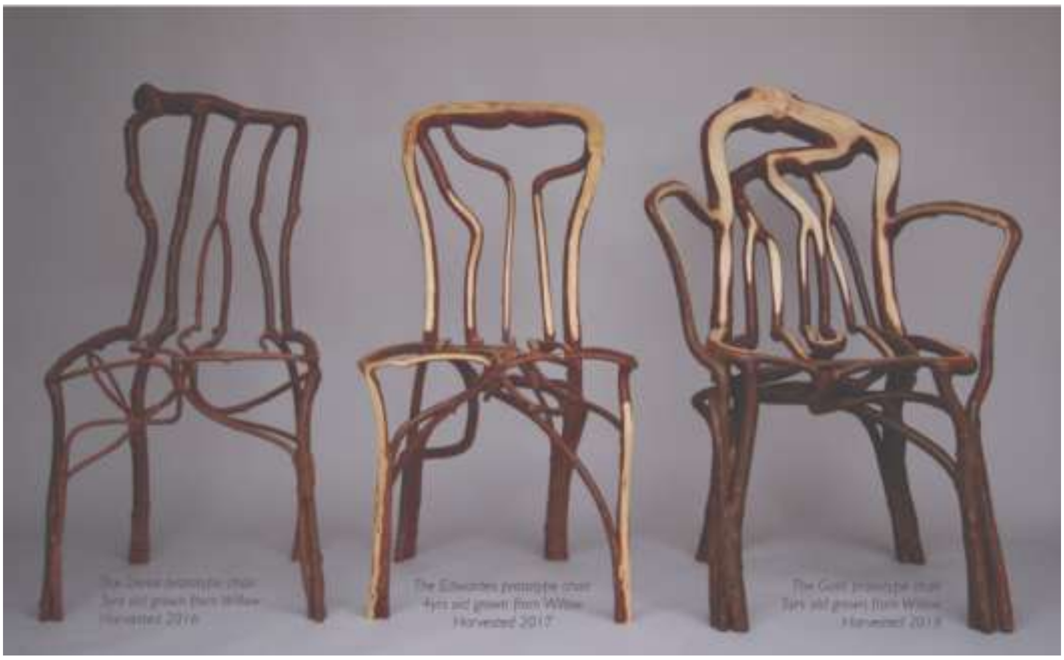

Figure 1. Chair designs by Fullgrown (https://fullgrown.co.uk/).

If biodesign is a practice with a lot of unique challenges to designers, those will reflect on its teaching and learning. In another work, we mapped how biodesign is addressed in formal education. We found 1 Masterclass for Professionals, 8 undergraduate courses, 1 undergraduate program, 4 master's, and 2 Ph.D. programs (Strobel do Nascimento & Heemann, 2023).

Whilst biodesign is being addressed in undergraduate programs in some universities, a systematic literature review (Strobel do Nascimento & Heemann, 2020) found no structured framework for facilitating the introduction of biodesign in undergraduate education. Given this research gap, the research question is formulated: How to facilitate teaching and learning the biodesign process (even) in a limited resource undergraduate education context? By limited resources, we mean the lack of a laboratory and a studio space. To answer this question, we describe the development and testing of a framework for facilitating the teaching and learning of the biodesign process in an undergraduate context with limited resources.

The next sections describe the methodological strategy, Design Science Research (DSR); following the description of the framework; and its evaluation at the Universidade Federal do Paraná`s Product Design undergraduate program; we discuss the results with other practices in formal education and conclude with propositions for future developments.

1. METHODOLOGICAL STRATEGY

This research was approved by the local ethics committee.

To develop the facilitation artifact, this study draws on the Design Science Research (DSR) methodological strategy described by Dresch et al. (2015). The approach has 12 phases that were clustered and organized in an adaptation of 5 phases, which are:

- Phase "1. Problem and Context" concerns the problem identification and awareness, which is supported by systematic and narrative literature reviews (Conforto et al., 2011; Ferrari, 2015; Green et al., 2006), as well as the attendance in related events, like symposiums and conferences. The main outcomes here are the concepts and terminology in the biodesign practice and the research context;

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- Phase “2. Related Artifacts” concerns the identification of artifacts related to the representation and description of the biodesign process and biodesign teaching and learning. The literature review is still an important methodological procedure at this point. 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 found in the literature. Each artifact was numbered, categorized, and organized into a table (see supplementary material “Related Artifacts and Insights”). Along with each artifact, insights for the framework were written down in one of the table`s columns. There were 59 insights in total;

- Phase “3. Development” relates to the design and development of the facilitation framework for teaching and learning the biodesign process. Each insight from Phase 2 was turned into 17 requirements, the requirements inspired 21 learning objectives created according to Bloom`s Taxonomy (Erasmus University Rotterdam, 2023) (see supplementary material “Framework`s requirements and learning objectives”). The framework was designed according to these learning objectives and to the pedagogical foundations of Charlotte Sörensen`s “Material Framework for Product Design. The development of reflective material practices” published in 2018. Besides the framework, an evaluation rubric to aid the instantiation in the next phase is developed, considering each learning objective (see supplementary material “Framework`s evaluation rubric”);

- In Phase “4. Evaluation” the artifact is evaluated. The evaluation of the framework happened in the Universidade Federal do Paraná’s mandatory course Materials and Processes III in the third year of the Product Design undergraduate program. The evaluation followed (i) the perception of the students regarding their learning concerning each of the learning objectives; (ii) the perception of the course professor upon the student`s learning regarding each learning objective; and (iii) the perception of this researcher’s Overt Observation (Gray, 2004), also concerning each learning objective. The analysis is made by triangulation according to Gray (2004). Thirty-seven students participated in the framework`s evaluation. 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.

2. FRAMEWORK FOR TEACHING AND LEARNING BIODESIGN

Figure 2 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 six 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 (see supplementary material “Framework application script”), a project journal (see supplementary material “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 (see supplementary material “framework evaluation rubric”). Activities consist of presentations of concepts and case studies; the use of the MA2E4 toolkit (https://materialsexperiencelab.com/); in-class brainwriting; orientation meetings, and activities in the project journal. The whole structure is supported by the pedagogical foundations according to Sörensen (2018). Finally, the learning outcomes are the learning objectives (see supplementary material). In the next paragraphs, we give some detail about the framework`s context-spaces, elements and materialities.

	Context Space Classroom		Context Space Student's Homes
Elements	1.Concepts 2.Repertoire 3.Project methodology	4.Practice 6.Reflections	5.Management
Materialities	Project evaluation rubric (for written feedbacks, framework evaluation rubric)	Application script, project journal, material samples for tests	Grow-it-yourself kit
Activities	Presentation of concepts Presentation of case studies and examples (repertoire) In class MA2E4, sensing and testing material samples In class brainwriting Individual orientation meetings		In the project journal: -Paper summarizing - Filled Microbioinspired catalog card *Ganoderma lucidum*; -Small acts of being *Ganoderma lucidum*; -Material's experience map (MA2E4) conclusions; - Design vision pattern (Material Driven Design) conclusions; -Moodboards; -In-class brainwriting conclusions; -Work Breakdown Structure; -Project timeline; - Product perceptual map; - Product competitor pricing map; - Tinkering monitoring 1, 2 and 3; - Conclusions on tinkering; - Empathy Canvas; - Sketches; - Final prototype monitoring; - Product price estimative; - Product commercialization strategy; - Product flyer; - Comparative timeline; - Project conclusions.

Charlotte Sörensen's Material Framework for Product Design (2018): Experiential learning theory (or learning-by-doing), Bloom's Taxonomy, Reflection-in-action, Creating learning environments, Open-ended assignments, Examples over rules, Use of toolkits, Structured exercises, Tinkering, Framing and reframing.

Pedagogical foundation

Learning outcomes

Understand, evaluate, analyze, apply, create

Figure 2. Framework for teaching and learning biodesign in undergraduate education. Elaborated by the author (2022).

Context-space (1) classroom refers to the classroom itself. At the Universidade Federal do Paraná, for example, it assumes the configuration of tables and chairs for the students on one side, and the lecturer standing on the opposite side. A blackboard and a light projector are available. The other context-space is the (2) students' homes, where tinkering and prototyping happens – activities that would normally be developed in a lab or a studio. Some activities happen at the intersection of those two context-spaces.

Concerning the framework`s elements:

- First, there is a repertoire of (1) Concepts to be explained to the students: these concepts may help them navigate important keywords, which makes it easier for them to later look for journal papers and information available – one example is the definition of "biodesign" itself;

- In addition to a repertoire of concepts, there is a (2) Repertoire of examples and (3) Project methodology. At this point, examples and case studies are presented, including the existing methods for designing in collaboration with other living organisms, like the “Material Driven Design” method (Camere & Karana, 2018);

- 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 product biodesign project and tinkering exercises with material samples and the 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 (see supplementary material), project presentations, and receiving feedback;

- In addition, (6) Reflections are made throughout the process: about ethics in designing with other living organisms, about empathy, and about the project itself.

Regarding 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 (Lazaro Vasquez & Vega, 2019; Monna, 2017; Parisi et al., 2016; Parisi & Rognoli, 2017; Weiler et al, 2019). For this project, a grow-it-yourself kit was prepared in partnership with the mycelium startup company Neomatter (Figure 3). The same company provided the material samples. 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. In the project journal (see supplementary material) each group plans their project, writes their conclusions of the activities after each class, monitors tinkering and prototyping developments, and strategically plans the product.

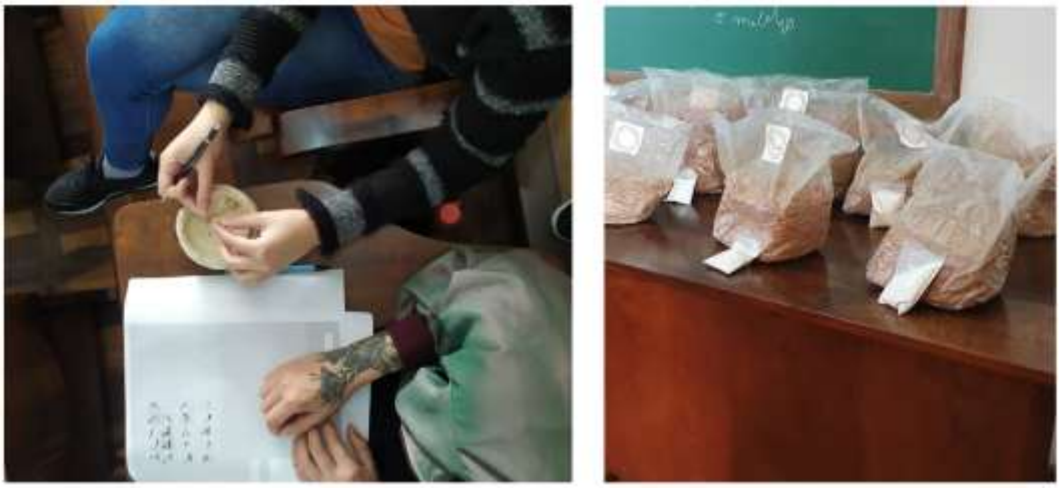

Figure 3. In the left, students the devolpment of the MA2E4 toolkit, in the right, the grow-it-yourself kits.

Given the context-spaces, the framework`s elements, its materialities - six modules were arranged, distributing the learning objectives and activities through them. Each module is a class with additional activities for the students to elaborate at home. This organization resulted in the “Framework`s application script” (see supplementary material). The next section presents the framework`s evaluation.

3. EXPERIENCES IN BIODESIGN TEACHING AND LEARNING

The framework`s application and evaluation took place at the mandatory course Materials & Processes III, from July 21, 2022, to August 25, 2022 (six weeks). There were six presential lessons with additional activities for students to do at home, following the application script. Thirty-seven students joined in the activity, working in 8 groups of 4 people, one group of 3, and one group of 2. A physical copy of the project journal was handed over for students to use, along with its digital file. Each group developed a product design project with mycelium. The framework's application was accompanied by the course professor, by a student in the final year of the Bioprocess Engineering and Biotechnology course, and by the CEO of Neomatter mycelium startup. Students' projects were evaluated according to a rubric.

To evaluate the framework, we followed three approaches: (i) overt observation was registered following each learning objective; (ii) additionally, the course professor also evaluated the framework through the evaluation rubric; and (iii) in the sixth and last class, students were invited to evaluate the framework according to the same rubric. The overt observation, the student's framework evaluation results, and the evaluation by the course professor were later triangulated - the results and the triangulation are presented in Table 2.

The evaluation rubric is available at the supplementary material and was organized in six modules (regarding each of the six working weeks and classes), presenting the learning objectives for each module and a summary of the activities that were developed. For each learning objective, four rating options were available: 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 learning objective " (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" was rated three times for modules 2, 3 and 5.

The students` evaluation of the framework took about 1 hour. Thirty-one students were present at the moment and participated in this step. More than half of the students evaluated nineteen of the learning objectives as "A", met, and two of them as "AP", partially met (See Table 2).

The course professor also evaluated the framework using the evaluation rubric, making remarks for each module (see Table 2). She evaluated twelve of the learning objectives as "A", met, eight of them as "AP", partially met, and one of them as "NP", did not participate.

The triangulation was made upon the convergence of the results (see Table 2): of the twenty-one learning objectives, fourteen were considered met and the other seven were concluded as partially met.

Table 2: 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 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;	NA: 0; 0% AP: 1, 3% A: 29, 94% NP: 1, 3%	A	All three evaluations agree that the learning objective was met. 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;	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% NA: 3; 10% AP: 3, 10% A: 25, 80% NP: 0, 0% NA: 0; 0% AP: 4, 13% A: 26, 84% NP: 1, 3%	A (2.1) AP (3.1) AP (5.1)	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
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;	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 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

Table continues next page

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 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;	NA: 1; 3% AP: 8, 26% A: 22, 71% NP: 0, 0%	AP	Although most of the students marked this learning objective 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
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 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;	NA: 0; 0% AP: 11, 36% A: 19, 61% NP: 1, 3%	A	All three evaluations agree that the learning objective was met. 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

Table continues next page

After the triangulation of the results, the framework`s contingency heuristics were underlined according to Dresch et al. (2015). They relate to the formalization of the artifact's limitations considering the environment in the implementation phase (here, Phase 4 - Evaluation), the conditions of use, and the situations in which it will be useful (Dresch et al., 2015). The contingency heuristics for this framework are described below:

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

II. In a Product Design program;

III. In a class where biodesign has not yet been introduced;

IV. In a pedagogical context where students are less used to taking more responsibility and protagonism on the learning process;

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

VI. With the availability of a classroom;

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

VIII. With a prepared low-cost grow-it-yourself kit;

IX. With the participation of 37 students (with the indication of a limit of 40 students);

X. With the participation of 2 lecturers/professors;

XI. 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);

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

Regarding the generalization to a class of problems planned for Phase 5 – Conclusion - Donmoyer (2008) writes that small sample sizes might render generalizability difficulty in qualitative research. He argues that only consumers of a given research might be able to determine the transferability of one study to another. Considering Donmoyer's perspective, the class of problems in this study 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.

4. DISCUSSION

In Strobel do Nascimento and Heemann (2023) we systematically analyzed the content of courses and programs in formal education in biodesign. On the occasion, we analyzed 1

Masterclass for Professionals, 8 courses, 1 undergraduate course (Major), 4 master's, and 2 Ph.D. programs – and found eight highlights: (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. We now discuss the framework with these highlights.

Beginning with (1) lab work - 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 (http://www.diymaterials.it/database-test-2/; http://materialdesigners.org/; Parisi et al., 2017). We also believe that incorporating work in an actual lab in the framework could be optional, leaving the framework`s contingency heuristics open to more varied contexts.

The reflection on (2) ethical implications was incorporated into the framework with in-class provocations and through an empathy exercise from Heather Barnett (MAAT - Museum, 2020).

Although one of the big resource issues is space, the framework focused on hands-on activities that relate to a (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 – however, the framework`s context-space structure seems to have worked out.

Concerning the (4) interdisciplinary experience, it was a challenge for the framework, mainly because of application time constraints in this study. Nevertheless, we managed to include the participation of a Bioprocess Engineering and Biotechnology student and the CEO of a mycelium startup company. However, the participation of more actors is encouraged for future framework applications.

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. In the framework application, we addressed this highlight by providing students with a grow-it-yourself kit for tinkering and also prototyping.

Regarding 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 and performed in the project journal. With these tools students could think of their products in a production-circulation-consumption context. We understand that in such an experimental and short experience the results of this approach could be limited, however, we see that it is important for the students to begin to think in production-consumption-circulation terms, like the other studied courses and programs in formal education in biodesign do. This brings forward the importance of commercial aspects for the students.

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. We believe that 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 offered to students who were already introduced in a previous biodesign course.

5. FINAL CONSIDERATIONS

Seeking to answer: "How to facilitate teaching and learning the biodesign process in a limited resource undergraduate education context?" - this study articulated the methodological strategy of Design Science Research to achieve a facilitating framework for teaching and learning the biodesign process. Except for the participation in the Biodesign Challenge, all highlights found in formal education were addressed to some degree by the framework.

Further ideas to be developed include, for instance, an advanced application of the framework in a special elective course instead of the 6 weeks inside an existing course. The advanced application 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; and a (7) following special course for participation on the Biodesign Challenge with interdisciplinary students. Future developments 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.

In conclusion, 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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