Relive: novel design approaches to livingness

Edited by

Venere Ferraro and Giorgia Burzio

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ISBN e-book Open Access: 9788835179306

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Preface

My first encounter with the project RELIVE happened on a warm June afternoon in Boston – a kind of day that, unlike the sun-soaked ones in Italy, is rare and fleeting, best spent near the ocean or under a canopy of trees. Still, I couldn't pass up an invitation from Venere Ferraro, a design researcher and expert in interaction and textile design, to discuss what it means to design with *living* and *livingness*, and here I was biking across the city to a crowded office to join the conversation.
The diversity of fields represented between the three of us around the table mirrored the diversity of fields now engaging in design with living and *living-like* artefacts. My own background spans biology, architecture, computational design, and synthetic biology. My collaborator Neel Joshi, who pioneered the field of Engineered Living Materials has expertise in chemistry, chemical biology, and synthetic biology. It quickly became clear that although we shared a common vision of designing living artefacts, a one-hour conversation wouldn't be nearly enough for us to untangle what we mean when we say artefact is *living*, *living-like*, *programmable*, *responsive*, or *regenerative*.
This conversation – like so many others that Venere Ferraro and

Giorgia Burzio, the editors of this book have hosted in the various formats of workshops, interviews, and conferences – revealed just how urgently we need shared language and frameworks to design with *livingness*. That's precisely what makes this book so timely and significant: it offers a common ground for exploring *livingness* as both a conceptual lens and a set of material capabilities. And more importantly, it does so from a design research perspective, as most contributors come from primarily design disciplines.
This vantage point shifts the conversation – not what the future of livingness *could* be from a technical perspective of enabling technologies, but toward what it *should* enable in terms of new human experiences, meaningful interactions, and healthier relationships with our environments. Can *livingness* become a means through which artefacts participate in mutualistic, even symbiotic, relationships with users and the environment around them?

Structured in two parts, the book begins by laying out foundational concepts of livingness and mapping its application across design in its many domains – healthcare, interaction, textiles, and reimagining traditional crafts. It then moves into practice-based case studies that illustrate the rich possibilities of living artefacts – from healthcare applications that explore microbial systems, to wearable fashion as living textile ecosystems, to speculative design for water purification, regenerative materials for yacht interiors. Each chapter brings unique perspectives but shares a commitment to reimagining design in relation to life itself.

For researchers and practitioners in design, HCI, synthetic biology, and architecture, this book offers a framework for cross-disciplinary inquiry and collaboration. For students and educators, it provides a toolkit for exploring this emerging domain – rich with both methodological depth and creative possibility. For those working in industry, particularly within the Made in Italy sectors, it reveals how *livingness* can reinvigorate tradition and craft through new technologies and material approaches.

The book invites all of us – across disciplines and practices – to consider how we might design with life.

Katia Zolotovsky
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Introduction

Venere Ferraro
Politecnico di Milano

In an era defined by ecological crisis and material scarcity, design must move beyond *extractive, disposable models* to embrace *livingness*—a paradigm that redefines artefacts as *adaptive, evolving, and regenerative entities*.

The book *RELIVE: NOVEL DESIGN APPROACHES TO LIVINGNESS* aims RELIVE to present the result of a research project executed at Depertment of Design of Politecnico di Milano and funded by Fondo d'Ateneo per la Ricerca di Base (FARB). The research started on November 2023 and finished in April 2025.

It aimed at exploring and conceptualizing a framework for designing *living artefacts* through living materials and digital technologies. The research seeked to redefine the role of materials in design, moving beyond passive substrates toward *dynamic, evolving entities* that interact with their environments.

The present book proposes a *new conceptual and methodological framework* for designing *living artefacts* by integrating *living materials and digital technologies*. By applying this research within the *Made in Italy system*, the book explores how the intersection of *biodesign,* *craftsmanship, and digital fabrication* can contribute to *sustainable innovation and ecological transition*.

The work presented in this book builds on *recent experimental research, speculative design, and emerging technological advancements* to propose a *new material paradigm* – one in which artefacts are not mere objects but *co-existing, evolving entities*. By challenging traditional notions of material stability and permanence, this research opens up *new possibilities for circularity, adaptability, and regenerative design*. The ultimate goal of this book is to provide *designers, researchers,* with the *tools, methods, and frameworks necessary to integrate livingness into their work*, ensuring that future design innovations *support ecological transitions and foster more symbiotic relationships between materials, users, and environments*.

By bridging *theory and practice, scientific research and design experimentation*, this book positions *living artefacts* as a *critical tool in the transition toward more sustainable, adaptive, and ecologically integrated futures*. Through its multidisciplinary lens, it invites *designers, scientists, and technologists to reimagine materials, artefacts, and their relationships with the world*, fostering a *new era of material agency that embraces livingness as a fundamental principle in design*.

At the core of this work is the *development and validation of a framework* that enables designers to engage with *living materials – biological, engineered, and programmable – as active, interactive elements in design practice*. This research builds upon *advancements in biodesign, synthetic biology, and digital fabrication*, extending the concept of *livingness beyond material properties* to examine its *experiential, interactive, and ecological dimensions*.

This book stands at the intersection of *design, technology, and biology*, offering a *structured yet flexible approach* for incorporating livingness into design processes. By structuring the *design process around living materials, digital fabrication, and bio-digital hybrids*, this framework offers a foundation for designers, researchers, and industry professionals seeking to incorporate livingness into their practice. The book presents *case studies, theoretical explorations, and design experiments*, illustrating the diverse ways in which living artefacts can be integrated into fields such as *fashion, architecture, product design, healthcare, and human-computer interaction (HCI)*.

More in details, it provides:

- a *Theoretical Framework* – Introducing *living materials as a fundamental shift in material agency*, expanding sustainability beyond biodegradability to include *self-sustaining and co-evolving material systems*;
- *44 Case Studies* – Mapping the application of livingness across fashion, architecture, healthcare, human-computer interaction (HCI), and product design, demonstrating its real-world potential;
- the *description of three Design Workshops* – Conducted as part of this research, the workshops tested the proposed framework, engaging designers, scientists, and technologists in *hands-on explorations of biofabrication, responsive materials, and living artefacts*. These workshops provided *critical insights into the practical challenges and opportunities* of designing with livingness, shaping the refinement of the framework.

By merging *scientific research, speculative design, and hands-on experimentation*, *RELIVE* establishes a *practical foundation* for integrating *biological intelligence into contemporary design practice*.

By embedding *livingness* into different design contexts, the book proposes a *radical departure from conventional design* – moving beyond *static, finite products* toward *dynamic, responsive, and self-sustaining artefacts*. This research explores how the integration of *biofabrication, smart textiles, and digital manufacturing* can *products* into *adaptive, regenerative systems* that extend beyond sustainability toward *ecological intelligence*.

PART 1

Livingness from theoretical foundation to relevant fields of application

1. Livingness and living artefacts in design process

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ABSTRACT

This chapter explores the concept of *livingness* in design, particularly through the creation of living artefacts – objects that integrate life-like qualities using natural, engineered, and programmable materials. By leveraging insights from several scholars exploiting livingness from different disciplines spanning from biology to design and human-computer interaction and the results of the Erasmus+ DATEMATS[1] project, the author proposes a refined framework for designing with living materials, grounded in the. Additionally, a discussion from semi-structured interviews with designers and researchers, reflecting on the challenges, opportunities, and implications of integrating livingness into design, follows. The study contributes to advancing sustainable and regenerative design practices by redefining interactions between humans, materials, and the environment. The framework presented has also been tested and validated in three design workshops.

Note 1. DATEMATS project (Knowledge & Technology Transfer of Emerging Materials & Technologies through a Design-Driven Approach Agreement Number: 600777-EPP-1-2018-1-IT-EPPKA2-KA) is co-funded by the Erasmus+ programme of the European Union.

1.1 Introduction

The notion of *livingness* is fundamentally reshaping the way designers approach materials, artefacts, and the relationships they foster with users and the environment. Traditionally, materials were regarded as passive elements, valued for their physical, aesthetic, and structural properties but ultimately inert and unchanging. In contrast, living materials introduce dynamism, adaptability, and organic interactions into the design process, necessitating a fundamental shift in how we conceive of material agency, functionality, and sustainability.

This shift towards designing with livingness emerges from the confluence of advancements in biotechnology, synthetic biology, responsive materials, and computational design. These developments have given rise to novel materialities that are capable of growing, self-healing, adapting, and interacting with their surroundings. The implications of this are vast, spanning from biodegradable materials that decompose naturally into ecosystems to biohybrid systems that blur the boundary between artificial constructs and biological life forms. This evolution in design is not merely about material innovation; it represents a profound philosophical and methodological transformation that questions the very nature of the designed object, its temporality, and its agency.

As designers embrace living materials, they must also confront new challenges. Working with materials that grow, change, and decay requires iterative experimentation and interdisciplinary collaboration with biologists, engineers, and computational scientists. Unlike conventional manufacturing processes, which rely on stability and predictability, designing with livingness necessitates a degree of openness to uncertainty and co-creation with biological entities. Furthermore, ethical considerations surrounding the manipulation and use of living systems introduce complex discussions about responsibility, sustainability, and the agency of non-human organisms in the design process.

This chapter explores how different levels of livingness – ranging from naturally occurring biological materials to engineered and programmable matter – contribute to the creation of living artefacts. Through a detailed discussion of the DATEMATS framework, we provide a structured methodology for incorporating living materials into design.

Additionally, we analyse findings from semi-structured interviews with designers and material researchers, highlighting the opportunities and challenges of working with living artefacts.

1.2 Approaching livingness in the design process

The concept of livingness in design is deeply intertwined with new materialist and post-anthropocentric philosophies that challenge the dominance of human-centered approaches to material agency. Scholars such as Jane Bennett (2010) argue for an expanded view of materiality that recognizes the vibrancy and agency of non-human entities, positioning materials as active participants rather than passive substrates. This notion resonates with Barad's (2003) *agential realism*, which suggests that materials do not merely exist in a static state but continuously perform, respond, and engage with their surroundings.

The *material turn* in design research, as outlined by Karana *et al.* (2015), further reinforces the idea that materials should not be understood solely in terms of their physical properties but as experiential and interactive agents. Within this framework, livingness extends beyond the biological realm to encompass any material system that demonstrates self-sustaining, responsive, or evolving characteristics. Whether biological or synthetic, living materials introduce temporal dynamics, meaning that designers must consider how materials will behave over time rather than treating them as fixed elements.

1.2.1 Expanding the definition of livingness in design

Building on these theoretical foundations, the notion of livingness in design can be categorized into different levels that reflect the degree of biological or artificial intelligence embedded in a material system. These categories include natural matters, engineered living materials and programmable matter, each of which plays a different role in shaping the future of material interaction and adaptability.

Natural matter
Natural living materials consist of biological entities or materials derived from nature that retain their life-like properties. These include mycelium, bacterial cellulose, bio-based polymers, and algae-based composites. The work of Hutmacher and Dalton (2018) highlights the growing use of naturally regenerative materials in sustainable fabrication. Unlike static materials, these biological substrates can grow, self-repair, and degrade over time, requiring designers to adopt strategies that accommodate their ephemeral and evolving nature. Mycelium-based composites, for example, have been used in architecture as biodegradable alternatives to conventional building materials (Jones *et al*., 2020).

Engineered living materials
Engineered living systems involve biotechnological interventions that modify or enhance natural biological processes to introduce new functions. This category includes synthetic biology-based materials, such as engineered bacteria designed to produce biopolymers or colour-changing biofilms that respond to environmental stimuli (Loh *et al*., 2021). The rise of biofabrication techniques in tissue engineering and biomaterial science has further expanded the potential for creating hybrid systems that merge biology with design. A prime example is the work of MIT's Mediated Matter Group, which has pioneered bioprinting techniques to integrate living cells into architectural forms (Oxman *et al*., 2016).

Programmable matter
Programmable matter represents the intersection of computation, material science, and bio-inspired adaptability. Unlike natural or engineered biological systems, these materials do not contain living cells but exhibit life-like behaviors through responsive mechanisms. Examples include shape-memory alloys, self-healing polymers, and hydrogel-based actuators that change their properties in response to environmental cues (Kim *et al*., 2019). Advances in soft robotics and biohybrid systems have further contributed to the integration of responsive materials into wearable technology, architecture, and product design (Shepherd *et al*., 2020).

The integration of living materials into design reconfigures the relationship between users and artefacts, shifting from static interactions to dynamic, evolving engagements. Karana *et al.* (2020) propose the idea of materials experience, wherein the material itself becomes a central aspect of user interaction. This notion is particularly relevant for living materials, which require users to engage with their growth, decay, and behavioral changes over time. Unlike conventional products that remain unchanged until disposal, living artefacts introduce a new temporal dimension to the design process, emphasizing care, maintenance, and adaptation.

Recent studies in Human-Computer Interaction (HCI) have explored how bio-responsive materials can serve as interactive interfaces, allowing users to communicate with biological systems through chemical, mechanical, or digital inputs (Yao *et al.*, 2021). In wearable technology, for instance, biohybrid garments containing algae cultures enable users to track environmental pollution based on colour shifts in the living cells embedded in the textile fibers (Bergmann *et al.*, 2022). This approach aligns with the broader trend of adaptive and performative materials, where artefacts are designed to actively respond to human input, climatic variations, or internal metabolic changes.

1.2.2 Considerations in designing with livingness

The integration of livingness into design also raises significant challenges. Unlike traditional materials, living artefacts require continued care and ethical responsibility, particularly in the case of genetically engineered organisms or bio-digital hybrids. Scholars such as Ginsberg *et al.* (2014) emphasize the need for biodesign ethics, urging designers to consider the implications of working with living agents that possess autonomous functions.

Additionally, the sustainability potential of living materials depends on their biodegradability, ecological impact, and long-term resource consumption. While many living materials offer promising alternatives to synthetic plastics and industrial composites, challenges remain in scaling production while maintaining ecological integrity. The emerging field of circular biodesign seeks to address this by developing systems that support closed-loop material cycles, in which biological artefacts naturally decompose and reintegrate into ecosystems without generating waste (Mazzarella *et al*., 2021).

By framing livingness as both a material and a process, designers can move beyond conventional material categories to develop adaptive, resilient, and regenerative artefacts that challenge traditional design paradigms. The integration of livingness into artefacts represents a shift towards co-evolutionary design, where materials and users exist in a continuous cycle of adaptation and mutual transformation.

1.3 A comprehensive framework for living artefacts

The development of a comprehensive framework for living artefacts is essential for guiding designers, researchers, and practitioners in the integration of biological and responsive materials into the design process. This framework stem from the methodologies and principles coming from Erasmus+ DATEMATS project coordinated by the author of this chapter (Ferraro V., 2021). This chapter outlines how these principles have been adapted to account for the specific complexities and affordances of living materials. The framework foresees three main blocks:

Understanding (analysis phase)

The first phase of this framework revolves around understanding the intrinsic properties of living materials, their behavior over time, and their interaction with environmental conditions. In *Designing with and for Emerging Materials*, the analysis phase is emphasized as a necessary foundation for designers to move beyond material selection towards an active dialogue with materials. When applied to living artefacts, this necessitates an interdisciplinary approach, requiring collaboration between designers, biologists, chemists, and engineers to map the possible applications and limitations of bio-integrated materials.

This phase also focuses on identifying key biological, ecological, and computational characteristics that may influence material selection and design interventions. Living artefacts do not follow a linear development process, as seen in traditional materials. Instead, they require an iterative, knowledge-driven approach that incorporates empirical observations, experimental research, and cross-disciplinary learning.

In the context of emerging materials design, Karana *et al.* (2020) discuss the necessity of material-driven design, in which material characteristics define the potential applications rather than traditional form-first approaches. This principle is even more relevant in the realm of living materials, as designers must work within the parameters set by biological systems, ensuring that growth cycles, sustainability, and ecological compatibility are central to their design decisions.

Shaping (experimentation phase)

Once the initial understanding of the material properties is established, designers move into an active experimentation phase, where biofabrication, digital manufacturing, and programming of living materials take place. The shaping phase is informed by both traditional prototyping techniques and experimental methods specific to biological materials, such as microbial cultivation, tissue engineering, and responsive material embedding.

This framework highlights that material innovation often happens through hands-on engagement and iterative prototyping, allowing designers to understand not just the aesthetic and mechanical properties of a material but also its performative and interactive qualities. This is particularly crucial for living artefacts, where the behaviour of the material over time – such as its response to light, moisture, and mechanical stimuli – must be explored and documented in real-world conditions.

In this phase, digital tools and bioengineering techniques are leveraged to enhance the adaptability of living artefacts. The feedback loops between biological growth and digital programming enable the development of hybrid artefacts that merge organic and artificial intelligence-driven behaviours.

Applying (synthesis phase)

The final phase involves the practical application and integration of living materials into real-world contexts, ensuring that ethical, functional, and user-centered considerations are embedded within the design process. This synthesis phase builds on the methodologies outlined in Ferraro V. (2021), emphasizing how materials interact with users, evolve in situ, and demand different modes of care and maintenance compared to traditional design objects.

Living artefacts introduce new time-based interactions, where their lifecycle must be anticipated and incorporated into the design; artefacts with embedded living systems require strategies for maintenance, regeneration, and eventual decomposition, marking a radical departure from traditional product lifecycles that end in disposal.

Additionally, this phase explores the ethical and sustainability dimensions of working with living materials. Ethical concerns related to bio-design, genetic engineering, and bioethics must be assessed, ensuring that living artefacts are designed responsibly and with respect to ecological integrity. The concept of designing for material agency, discussed extensively in emerging materials research, is particularly relevant for living artefacts, as they challenge conventional ideas of ownership, authorship, and user control.

1.3.1 Adapting the framework for living artefacts

By integrating the above-mentioned principles designers working with living artefacts can better structure their methodologies while accounting for the unique affordances and challenges presented by biological materials. The adaptation of this framework acknowledges that living artefacts are not static objects but co-evolving, responsive systems that require continuous refinement and interdisciplinary input.

The following considerations further refine the approach: Material Adaptability Over Time – Unlike static materials, living artefacts change in response to their environment, requiring designers to implement monitoring and maintenance strategies; Multi-Stakeholder Collaboration – The inclusion of biologists, material scientists, ethicists, and computational designers is critical to creating successful living artefacts; User and Context Awareness – The integration of living materials must align with cultural, environmental, and technological considerations, ensuring that they serve meaningful purposes beyond aesthetic innovation. Author proposes a comprehensive framework that establishes a structured yet flexible model for designing with living artefacts, equipping designers with the tools to create materials that are dynamic, adaptive, and sustainable within their broader ecological and social ecosystems.

This framework consists of three key phases.

1. *Understanding* (Analysis): this phase focuses on researching material properties, biological behaviours, and potential design applications. It involves interdisciplinary collaboration to assess how living materials function within specific environmental and contextual parameters.
2. *Shaping* (Experimentation): this phase emphasizes hands-on material manipulation, bio fabrication, and iterative prototyping. Designers engage in processes such as microbial cultivation, and material hybridization to explore how living materials evolve over time.
3. *Applying* (Synthesis): the final phase integrates living materials into functional applications, addressing user interactions, ethical considerations, and long-term sustainability. Designers must consider factors such as biodegradability, maintenance, and the lifecycle of the living artefact.

The following figure illustrates the adaptation of the DATEMATS framework to living artefacts.

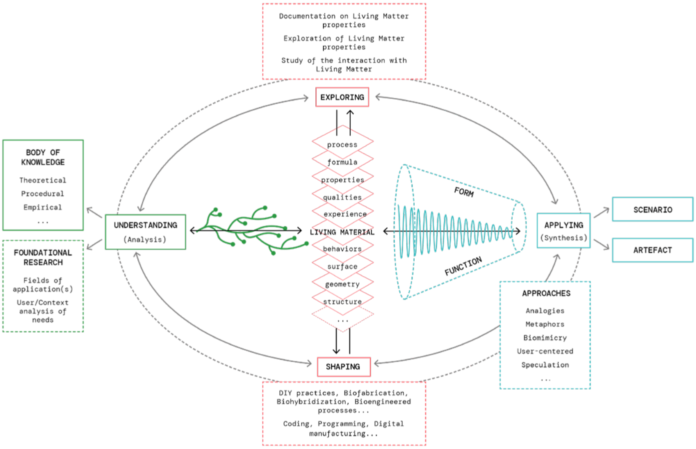

Figure 1.
A comprehensive framework to design living artefacts.

1.4 Confirming the framework: semi-structured interview

To validate the framework and gain a deeper understanding of how living artefacts are perceived and implemented in design practice, a series of semi-structured interviews were conducted with seven professionals working in diverse fields related to living materials. The interviewees included designers, material scientists, biologists, engineers, and interaction designers, reflecting the interdisciplinary nature of this domain. Their expertise spanned biodesign, synthetic biology, human-computer interaction (HCI), biomimicry, and digital fabrication, ensuring a holistic view of the current challenges and opportunities within this emerging area of design.

The interviews followed a semi-structured format, allowing for open-ended responses while maintaining a focus on key research areas. The main topics of inquiry included:

1. How do you work with living systems to prototype or develop living artefacts?
2. What challenges do you face in designing living artefacts, particularly regarding material behavior, scalability, and integration into design processes?
3. Which sectors do you see as the most promising for the application of living artefacts?
4. Do you find the proposed framework for designing with living materials useful? If not, what modifications would you suggest?

Interviews were conducted remotely via video conferencing over a period of six weeks, and each session lasted approximately 45 to 60 minutes. The qualitative data collected was then transcribed and thematically analysed to identify recurring themes, insights, and potential areas for further exploration.

1.4.1 Challenges in designing living artefacts

A significant challenge identified across multiple interviews was the unpredictability of biological systems when integrated into design. Unlike traditional materials, which behave in stable, measurable ways, living materials introduce an element of variability, requiring designers to develop adaptive methodologies and new evaluation criteria. This unpredictability makes it difficult to scale living artefacts for commercial production while maintaining their biological functionality and responsiveness.

Another major challenge discussed was the lack of standardized fabrication processes for living materials. While digital fabrication techniques, such as 3D bioprinting and microbial culturing, offer innovative ways to integrate living systems into design, they are not yet fully optimized for industrial applications. Several interviewees highlighted the need for new tools and protocols that bridge the gap between experimental laboratory work and practical design applications.

The question of who is responsible for maintaining or disposing of living artefacts remains a grey area, prompting a need for clear regulatory frameworks and ethical guidelines for biodesigners.

Promising sectors for living artefacts

Despite the challenges, participants identified several promising sectors where living artefacts could have the most significant impact:

1. fashion & wearable technology: Living artefacts hold immense potential in fashion and wearable technology. Interviewees discussed the integration of living textiles, such as biohybrid garments embedded with microorganisms that change colour based on air quality or biofabricated materials that regenerate over time;
2. healthcare & biomedical applications: The use of engineered living materials for wound healing, medical implants, and drug delivery systems was a key area of interest. Living artefacts in this sector could enhance biocompatibility, sustainability, and patient-centered innovations. Many participants saw potential in using living materials to create self-healing surfaces, biodegradable consumer products, and adaptive textiles that respond to environmental changes. Materials such as bacterial cellulose, mycelium-based leather, and algae-derived bioplastics were cited as particularly promising.

1.4.2 Framework validation and recommendations

Most interviewees – five out of seven – expressed strong support for the three-phase structure of the framework, particularly appreciating its ability to systematically address the complexities of working with living materials. They found the framework to be a useful tool for structuring workflows, particularly in interdisciplinary projects where collaboration across scientific and design fields is necessary. They noted that the Understanding phase effectively facilitates material exploration, while the Shaping phase allows for experimental iterations and refinement before moving into the Applying phase, where the artefact is fully integrated into design contexts.

Living materials, by their nature, are not static entities; they evolve over time, requiring continuous adaptation and reassessment, for these reasons all participants appreciated the more iterative process.

One participant, a biodesign researcher, emphasized that «designing with living systems is not a one-directional process but a continuous negotiation between biological behaviour and design intent». This underscores the need for feedback loops and iterative prototyping cycles within the framework to ensure adaptability at every stage.

Several participants noted that while the existing framework effectively guides the development and application of living materials, it does not fully address post-use considerations. Given the temporal nature of living artefacts, questions arise about their long-term viability, degradation, and integration into ecological systems. Some experts suggested that designers should incorporate biodegradability, regenerative properties, and post-use material reintegration into their design strategies to align with sustainability and circular design principles.

Additionally, interviewees highlighted the need for sector-specific adaptations of the framework. While the general structure provided a solid foundation, several participants emphasized that different industries require tailored approaches. For instance, those working in fashion and wearable technology stressed the importance of understanding how living textiles interact with human skin, movement, and environmental exposure, while those in architecture and built environments focused on the structural and climatic adaptability of bio-integrated materials. Similarly, experts in healthcare and biomedical applications underscored the significance of biocompatibility and patient safety in medical grade living materials.

Overall, the validation process reinforced the framework's relevance and applicability, while also revealing key areas for further refinement. The integration of iterative cycles, lifecycle management strategies, and industry-specific adaptations will be crucial in ensuring that the framework remains a dynamic and evolving tool that reflects the complex realities of designing with living artefacts.

Regarding the proposed framework, five out of seven participants expressed strong support for its three-phase structure (Understanding, Shaping, and Applying). They found it to be a useful tool for navigating the complexities of working with living materials. However, four participants suggested that the framework should be more flexible and iterative, allowing for continuous feedback loops rather than a linear process.

1.5 Conclusions and further development

The exploration of livingness in design has underscored a profound shift in the way materials, artefacts, and their interactions with users and the environment are conceived. The findings presented throughout this chapter demonstrate that the integration of natural, engineered, and programmable materials is not merely a technical challenge but a conceptual and philosophical transformation in design thinking. As this paradigm continues to evolve, it demands a new material literacy – one that acknowledges the dynamic, responsive, and often unpredictable nature of living artefacts.

Through the application of the DATEMATS framework, it is evident that designers must adopt interdisciplinary strategies that combine biological expertise, computational modeling, and interactive design methodologies. The iterative, multi-phase approach presented in this framework enables designers to move beyond traditional static materials, allowing them to work with materials that evolve, adapt, and in some cases, regenerate over time. This shift aligns closely with growing global concerns around sustainability, circular design, and responsible innovation, positioning living materials as a key driver for future material and design evolution. One of the most critical insights from the semi-structured interviews was the necessity of rethinking the role of the designer. Unlike traditional product development, which focuses on pre-determined material behaviours, designing with living materials requires continuous co-development and interaction with biological systems. This means that designers are not only creators but also facilitators, orchestrating conditions that allow living artefacts to thrive, function, and eventually decay in a controlled and meaningful way.

Moreover, the growing interest in cross-sector applications – from fashion and product design to healthcare and architecture – highlights the diverse potential of living artefacts. The ability of these materials to self-repair, biodegrade, or respond to environmental stimuli makes them uniquely suited for addressing some of the most pressing material challenges of our time. However, these advantages also come with challenges related to material standardization, scalability, and long-term lifecycle management. Without a dedicated framework for maintaining and integrating living artefacts into larger material ecosystems, their practical applications could remain limited to niche experimental domains.

The validation of this framework through expert interviews has reinforced the need for long-term studies, regulatory frameworks, and ethical discussions surrounding the use of living materials in everyday products. It has become clear that while living artefacts offer exciting new possibilities for sustainable design, adaptive functionality, and material intelligence, they also introduce new responsibilities for designers, manufacturers, and users. This includes considerations such as how living materials are cared for, their interactions with natural ecosystems, and the ethical implications of working with bioengineered or synthetic biological systems.

Ultimately, the future of livingness in design represents a paradigm shift that transcends material innovation, positioning designers not only as creators but as caretakers of material ecosystems. This new era of material agency challenges traditional notions of permanence and control, encouraging a more adaptive, symbiotic, and ecologically integrated approach to design. The principles established in this chapter offer a foundation for future exploration, guiding the development of living artefacts that are not only functional but also harmonious with the environments they inhabit.

The interviews reinforced the idea that designing with livingness requires an entirely new mindset, one that embraces uncertainty, adaptability, and interdisciplinary collaboration. As the field of living artefacts continues to grow, there is a pressing need for new material taxonomies, scalable fabrication techniques, and ethical guidelines that govern their implementation.

These findings provide valuable insights into the future direction of research and practice in this field. By addressing the challenges of unpredictability, scalability, and ethical responsibility, designers and researchers can push the boundaries of what is possible with design synthetic biology, and responsive materials. Furthermore, the growing interest in cross-sector applications – from consumer products to architecture and biomedical design – suggests that living artefacts will play an increasingly prominent role in shaping the material landscapes of the future.

The framework developed for integrating livingness into design has been validated in three design workshops, providing an empirical foundation for its application across various material domains. These workshops allowed researchers and practitioners to refine the methodology, incorporating real-time feedback from interdisciplinary teams working with living materials. (see chapter 2.1, 2.2 and 2.3)

Moreover, two of the most promising sectors – healthcare and fashion – have been further explored in separate chapters of this book (chapter 1.3 and 1.4). These case studies provide concrete examples of how living artefacts can be implemented in real-world design scenarios, offering valuable insights into material behaviour, scalability, and user interaction.

Acknowledgement

Author wants to thank the entire Research Group of the Project RELIVE. Moreover, a big thank goes to the researchers and pratitioners involved into the interviews namely, Lucrezia Alessandroni, Giulia Tomasello, Rosie Broadhead, Orkan Telhan, Elise Elsacker, Katia Zolowsky, Neel Joshii.

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2. Exploring livingness through case study: an annotated portfolio

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ABSTRACT

This chapter explores 44 case studies by designers, practitioners, and researchers engaging with livingness. Selected based on the proposed definition, these case studies were drawn from design platforms, academic records, research labs, and exhibitions. Presented as cards, they include a brief description, their actions/interactions and development process, the microorganism or technology responsible for its living properties, and their sector. Drawing on 'annotated portfolio', the chapter brings together these artefacts into a comprehensive body of work, highlighting similarities, and cross-field comparisons. The case studies were organized into a two-axis matrix: the horizontal axis categorizes the degree of living matter – natural, engineered, or programmable – while the vertical axis reflects the nature of the output – explorative, experimental, or validated prototypes. The mapping offers insights into emerging trends and on how different approaches explore livingness through practice.

2.1 Introduction

In previous research, attempts have been made to understand what defines livingness within living artefacts, what implications it has for design, and how living artefacts can be classified by their degree of livingness, purpose, and function. This exploration has drawn on different definitions of livingness from various academic backgrounds. For instance, Karana *et al*., (2023), from a design-oriented perspective, define livingness as «The intrinsic capacity of living organisms to regenerate, renew, or restore themselves, [which] has been harnessed within living artefacts predominantly to support specific functionalities or use scenarios». De Rossi & Ahluwalia, (2000), from a Human Computer Interaction perspective, describe living artefacts as «a biomimicked system of a living (natural) system», emphasizing the imitation of natural processes. Meanwhile, Peng *et al*., (2023), from a synthetic biology perspective, highlight that «Living materials represent a new frontier in functional material design, integrating synthetic biology tools to endow materials with programmable, dynamic, and life-like characteristics».

Building on these definitions, this chapter takes its theoretical foundation from the first chapter of this book, *Livingness and Living Artefacts in Design Process,* to further explore the concept of livingness from a practical standpoint.

To integrate the various nuances of these definitions, the methodology of annotated portfolio (Gaver & Bowers, 2012) is employed to examine a selection of case studies gathered from design platforms, academic records, research labs, and exhibitions. The case studies are mapped onto a two-axis matrix that compares the layers of livingness with the type of output. This approach allows for an organized comparison of works from practitioners with diverse backgrounds, highlighting cross-disciplinary connections and emerging trends. It provides a comprehensive perspective on how livingness is explored across disciplines, fostering a broader understanding of its possible applications.

2.2 Methodology

2.2.1 Case study selection

The 44 case studies were identified to explore how livingness is embedded within artefacts, based on selection criteria defined in relation to the different definitions of livingness identified in the literature, ensuring a comprehensive examination of the topic. The selection focused on three categories: Natural Matter, Engineered Matter, and Programmable Matter. This includes i) artefacts that integrate living organisms by extrapolating them from their natural environments (Natural Matter); ii) designs utilizing synthetic biology or other bottom-up approaches to manipulate living cells, enabling new functionalities or behaviors (Engineered Matter); and iii) artefacts that simulate life-like properties through programmable, dynamic, or adaptive materials, including bio-hybrid systems like soft robotics (Programmable Matter). By applying these criteria, the case studies were gathered from diverse sources, such as design platforms, academic records, research labs, and exhibitions. In selecting the case studies, efforts were made to achieve a balanced representation by choosing projects from diverse backgrounds, including design (product, architecture, interaction, fashion), Human-Computer Interaction, and synthetic biology. This was intended to prevent a skewed depiction of the heterogeneity of practitioners engaging with livingness.

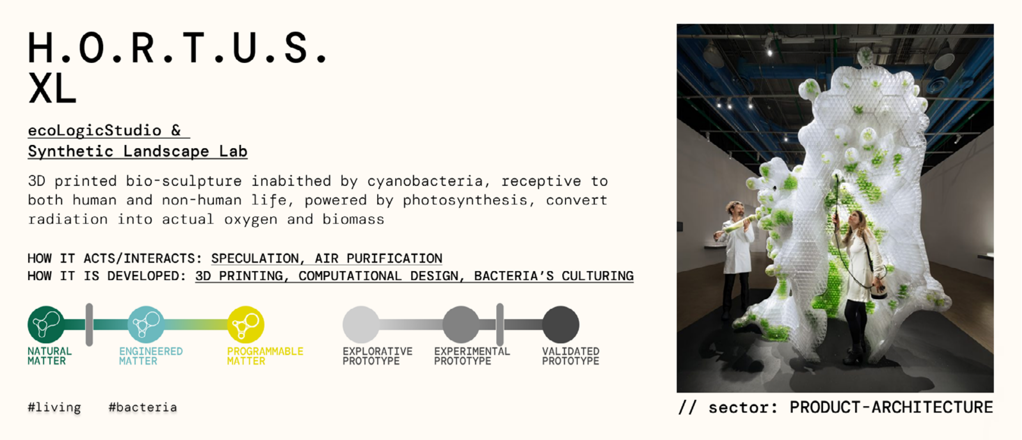
2.2.2 The annotated portfolio

The methodology of annotated portfolio was chosen for this research as it allows for a nuanced exploration of the selected artefacts while respecting the particularity and multidimensionality of design practice. Unlike formalized theoretical frameworks, this method enables a contextualized understanding of each artefact by linking its features to broader research concerns through targeted annotations (Gaver & Bowers, 2012).

In this study, annotations were crafted to systematically highlight each artefact's relevant characteristics. This is illustrated in Figure 1, which presents an explanatory example of a case study card (H.O.R.T.U.S. XL by ecoLogicStudio & Synthetic Landscape Lab). The annotations on the card include (from top to bottom, left to right):

- *title, author & description*: the artefact's name is prominently displayed, followed by the author(s), and short overview of the artefact's purpose and functionalities, emphasizing its interesting aspects (e.g., how H.O.R.T.U.S. XL converts radiation into oxygen and biomass using cyanobacteria);
- *how it acts/interacts*: this section describes the artefact's actions and/or interactions. In the example, it highlights the speculative nature of the installation (interaction) and its air purification functionality (action) powered by cyanobacteria;
- *how it is developed*: the processes/tools used in the development of the artefact are outlined. In the example, 3D printing, computational design, and bacteria culturing;
- *layer of livingness*: this annotation specifies where the case study is positioned on the spectrum between Natural, Engineered, and Programmable Matter (in this case, between Natural and Engineered Matter);
- *type of output*: it categorizes the artefact's design intent, ranging from an explorative prototype to a more validated one (in this example, between experimental and validated);
- *keywords*: key tags are included, such as #living and #bacteria, to facilitate thematic connections;
- *picture of the case study*: a visual representation of the artefact complements the textual annotations;
- *sector*: the sector to which the artefact belongs is specified (in this case, product-architecture).

Figure 1.
Case study card of ecoLogicStudio & Synthetic Landscape Lab, *H.O.R.T.U.S. XL*.
Complete list of the case studies card in Annex I.
Photo Credits from the authors of the projects.

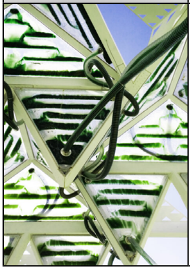


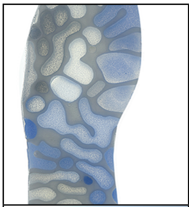
2.3 Case study

2.3.1 Case study cards overview

From the 44 case studies analyzed and collected in the annotated portfolio, 10 are now presented to provide an overview of the diverse approaches to livingness. They are shown in Table 1 using the same annotations as the case study cards, allowing for consistency and ease of comparison. The selected case studies come from different areas to provide a comprehensive perspective: design, synthetic biology, and HCI.

Table 1. Overview of selected case study cards (details after Reference sections). Photo Credits from the authors of the projects.

Case Study Image	Title, Author & Description	How it acts/ interacts	How it is devel- oped	Layer of livingness	Type of output	Key- words	Sector
	***Grow Your Own Couture***, Piero D'Angelo. Fashion garments integrating lichens to absorb air pollutants, delivered in a DIY kit.	Air purifica- tion	Growing design processes, biofabri- cation, diy methods	Natural Matter	In between Explorative and Experi- mental Prototype	#living #lichens	Fashion
	***Future Flora***, Giulia Tomasello, ALMA. A speculative har- vesting kit designed for create a hostile environment for the development of candida.	Preventing and treating vaginal infection	Bacteria's culturing, biofabri- cation, DIY methods	Natural Matter	Experimen- tal Prototype	#living #bacteria	Product
	***Spark of Life***, Teresa Van Dongen. Electrochemically active bacterias emit light and generate electricity into the *living lamp*.	Emitting light	Bacteria's culturing	In between Natural and Engi- neered Matter	In between Experimen- tal and Vali- dated Prototype	#living #bacteria	Product
	***Urban Algae Folly***, ecoLogicStudio. Interactive pavilion with living micro-algal cultures that absorb air-pollutant. The visitors can interact with the structure with their smart phones.	Air purifica- tion	Algae's Culturing in bioreactors	In between Natural and Engi- neered Matter	Experimen- tal Prototype	#living #algae	Product Archi- tecture

	***Deep Learning Insole***, PUMA + MIT Design Lab. Insoles that contain microbial cultures to monitor biochemical vitals, responding to the skin and sweat.	Giving feedback on user's performance	Bacteria's Culturing, Bio-hybridization processes, programming	Engineered Matter	Validated Prototype	#living #bacteria	Product Fashion Interaction
	***Skin II***, Rosie Broadhead. Encapsulated probiotic bacteria into the fibres of clothing. They activate when they come into contact with the moisture on skin.	Reducing odor, cell renewal, improving immune system	Textile techniques, bacteria's culturing, biofabrication	Engineered Matter	Validated Prototype	#living #bacteria	Fashion Health
	***Living Tattoo***, Xinyue Liu & MIT. 3D printed living tattoo made of bacterial-based hydrogel ink sensitive to a different chemical or molecular compound.	Coloring (feedback)	3d printing, genetical programming of bacteria, bio-engineering processes, protein engineering	Engineered Matter	Experimental Prototype	#living #bacteria	Interaction Fashion
	***Plug-and-play modular biobatteries***, Anwar Elhadad, Lin Liu & Seokheun Choi. A microfabricable and scalable biobattery that includes a microbial consortium.	Electricity generation	Programming, electro-biofabrication, Electro-polymerization	In between Engineered and Programmable Matter	Validated Prototype	#living #bacteria	Product
	***E. chromi: Living Colour from Bacteria***, Alexandra Daisy Ginsberg. Engineered bacteria, ingested in yoghurt, colonises human's gut, keeping watch for the chemical markers of diseases.	Colour changing (feedback)	Bioengineering processes, synthetic biology	In between Engineered and Programmable Matter	In between Experimental and Validated Prototype	#living #bacteria	Health
	***SELK's programmable textile actuators***, MotorSkins. Multilayered textile structure exemplifies programmable matter, endowing it with the ability to sense, react, and adapt to its surroundings.	Adaptation, physical reaction, movement	Soft robotics, fluid logic, programming, bio-inspired design, tissue mimicking	Programmable Matter	Validated Prototype	#soft robots	Interaction Fashion

2.3.2 Comparative insights

An analysis of the case studies reveals a broad spectrum of application areas and methods utilized by practitioners working with livingness. A wide array of tools and techniques emerges, including bacteria and algae culturing, biofabrication, DIY methods, textile techniques, bioengineering processes, programming, 3D printing, fluid logic, etc. The diversity in tools and methodologies reflects the varied backgrounds of the practitioners, whether they originate from material sciences, design, Human-Computer Interaction, synthetic biology, or a combination of these fields. This, in turn, defines both the type of output – be it Natural, Engineered, or Programmable Matter – and the unique ways in which they approach livingness.

The comparison also highlights different strategies for integrating living organisms into artefacts. In some case studies, their specific properties – such as bioluminescence, air purification, or electricity generation – are harnessed, as seen in *Spark of Life* and *Urban Algae Folly*. Additionally, some projects exploit the responsive nature of living organisms to provide feedback on health conditions or performance. For example, *E. chromi*, *Future Flora*, and *Living Tattoo* leverage color-changing properties triggered by environmental factors to communicate bodily conditions, while *Deep Learning Insole* offers performance-related feedback. Certain artefacts are designed to interact directly with the body's microbiome, such as *Skin II*, where encapsulated probiotics reduce body odor and enhance immune function, or *Future Flora*, a speculative kit designed to foster a protective microbial environment, intended for direct vaginal contact.

The keyword annotations reveal that a range of living organisms, including algae, lichens, and bacteria, have been employed, with bacteria emerging as the most frequently utilized across the case studies.

2.4 Mapping the case studies

2.4.1 The matrix and its structure

To facilitate the reading of the matrix, a compact version of the case study card was created, containing only essential information: the case study name, author, link, and a brief description. These cards were then positioned within the matrix according to the criteria defined by the axes, as previously explained. Figure 2 presents three examples of these simplified cards. This streamlined format allows for a clearer and more accessible overview of the selected case studies, supporting the cross-analysis conducted through the matrix.

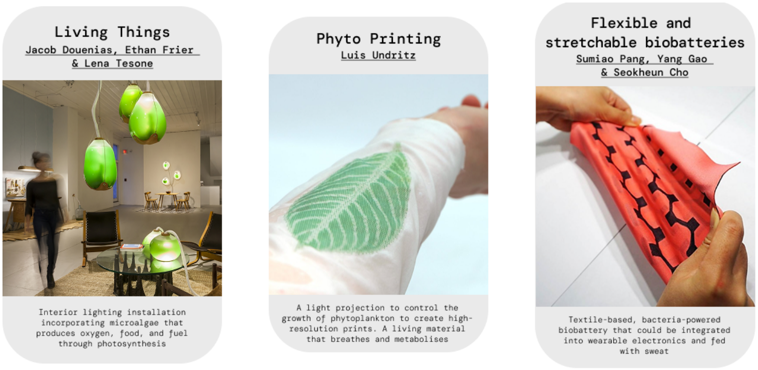
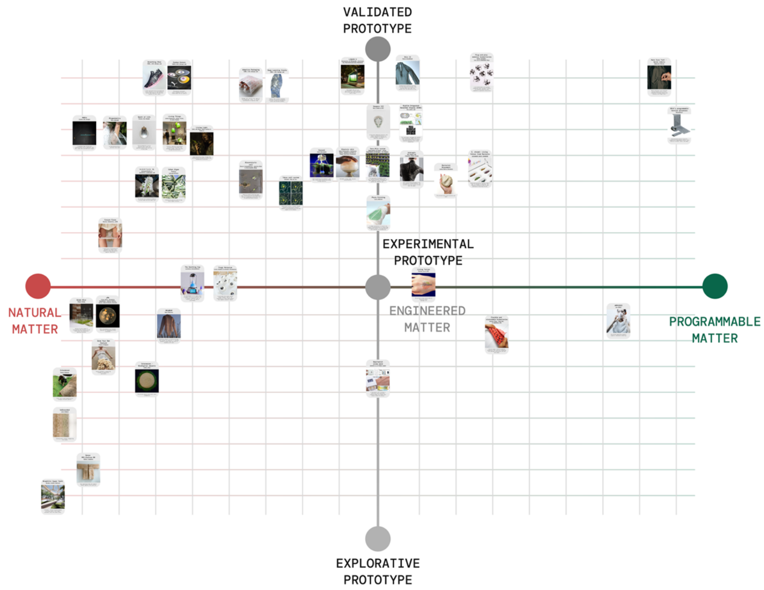


Figure 2.
Examples of compact case study cards (see Annex I). Photo Credits from the authors of the projects.

The matrix (Figure 3) is structured along two axes to organize and cluster the case studies. After extensive reflection on the most appropriate categories, the x-axis was defined using the parameters Natural Matter, Engineered Matter, and Programmable Matter, capturing the different natures of livingness, as discussed in Section 2.1. The y-axis categorizes the case studies by their type of output, using the terms Explorative, Experimental, and Validated Prototype. This categorization emerged after several iterations, including initial considerations of alternative terminology. For example, the term 'Speculative' was initially considered instead of 'Explorative' but was eventually discarded as it did not adequately capture the intended meaning. This decision was influenced by the observation that almost all projects dealing with livingness involve some form of speculative intention, making the term too broad for the purpose of this classification. Explorative Prototypes are primarily conceptual projects with an investigative approach, aiming to provoke reflection or open new research directions without necessarily demonstrating effective functional applications. Experimental Prototypes test materials, technologies, or processes to evaluate feasibility and explore behaviors or interactions, contributing to ongoing development and iteration. Validated Prototypes have demonstrated reliable functionality through testing in real contexts, showing consistent performance and readiness for further development or implementation, with some already commercialized or close to market entry.

Figure 3.
Case Studies Matrix (complete list of the case studies after Reference sections). Photo Credits from the authors of the projects.



2.4.2 Emerging trends in livingness

An analysis of the case studies' distribution within the matrix highlights emerging trends in the application of livingness. Certain areas are notably more populated, particularly the Engineered Matter area between Experimental and Validated Prototypes (center-top of the matrix), the Natural Matter area between Experimental and Validated Prototypes (top-left), and the Explorative Prototypes within Natural Matter (bottom-left). In contrast, the Programmable Matter-Explorative Prototypes area (bottom-right) remains largely empty, with only a few case studies appearing in the Programmable Matter Experimental-Validated Prototypes area (top-right).

The first area identified (center-top of the matrix) suggests that many projects engaging with livingness focus on the creation of artefacts and materials manipulated at the cellular or molecular scale through human intervention, employing methodologies and tools rooted in synthetic biology and bioengineering. These projects engineer materials with tailored functional properties, absent in natural materials, or enhance the characteristics of natural materials for specific technical applications. Notable examples in this area include case studies such as *BioLogic*.

BioLogic, developed by MIT Media Lab & Tangible Media Group, is self-transforming biological skin activated by living bacteria, the *Bacillus Subtilis Natto,* harvested in a bio lab. The synthetic bio-skin reacts to body heat and sweat. This project embraces a seamless integration of biological and engineering approaches, fostering a fluid synergy between the two disciplines.

The second identified area (top-left of the matrix) highlights that many living artefacts classified as Validated Prototypes involve Natural Matter – case studies in which the living organism is integrated into the artefact in its natural state, with minimal or no human intervention, and its properties are utilized until it undergoes natural decay or death. Representative projects in this area include *Ambio*.

Ambio is a swinging lamp, designed by Teresa Van Dongen, that harnesses the natural bioluminescence of micro-organisms. When exposed to oxygen, these organisms emit light, creating an interactive illumination system that smoothly blends design and biology. This artefact relies on the intrinsic properties of living matter, until its biological cycle reaches completion.

The third identified area (bottom-left of the matrix) is predominantly composed of conceptual projects that adopt an investigative approach, with the primary goal of stimulating critical reflection on the possibilities and implications of livingness in design. These projects often explore theoretical or speculative ideas rather than focusing on practical application. In this area, projects such as *Interwoven* can be observed.

Interwoven, developed by Diana Scherer, investigates plant roots as active agents in living textile production. The project intersects art, design, and biotechnology, exploring root system domestication. The roots are shaped into specific patterns, challenging traditional cultivation and design, and blurring the line between the natural and the manufactured matter.

The underpopulated areas of the matrix further support existing literature, which highlights that programmability within materials is still a largely unexplored domain. In this context, projects like *Nano Cure Tech Nylon Fabric* and *SELK Programmable Textile Actuator* emerge, showcasing life-like properties such as self-healing and soft actuation. The *Nano Cure Tech Nylon Fabric*, developed by Imperial

Motion harnesses a water-resistant nylon material that has the capability of self-repair, responding to mechanical damage by self-healing. The *SELK Programmable Textile Actuator*, developed by Motor Skin, explores soft robotics and programmable matter, enabling textile structures to sense, respond, and adapt to their environment.

The emerging trends in the application of livingness across these case studies reveal a deeper focus on integrating biological and engineered materials by practitioners. While areas such as engineered and natural matter are well-explored, programmable matter remains underdeveloped, pointing to significant potential for future exploration and research.

2.5 Conclusion

This chapter examined 44 case studies within a two-axis matrix to map how livingness is embedded in design and research practices, revealing a diverse and heterogeneous landscape of approaches across Natural, Engineered, and Programmable Matter. The analysis of the matrix highlights that while many projects focus on biological and/or engineered materials, the potential of programmable materials remains largely unexplored, presenting a promising area for future research.

This work provides designers with a nuanced selection of case studies demonstrating how living materials can be embedded in artefact design – not only as functional elements but also as drivers for rethinking material agency and responsiveness. For HCI practitioners, the analysis highlights how biological and programmable materials can perform as active interfaces, mediating interactions between users, artefacts, and environments through dynamic feedback. In materials science, this research underscores the need to move beyond a static conception of matter, reconsidering materials as adaptive, evolving, responsive, and inherently alive.

The use of an annotated portfolio as a methodological tool allowed for a structured yet flexible analysis, preserving the specificity of each case while drawing broader connections. Unlike rigid theoretical models, this approach captures the diverse, situated nature of design and research artefacts. Annotations shape interpretation, highlighting critical themes and uncovering latent patterns that might otherwise remain unnoticed (Gaver & Bowers, 2012). In the context of this research, the annotated portfolio was instrumental in mapping how different conceptualizations of livingness manifest across artefacts, highlighting similar approaches and underexplored areas, revealing trends, gaps, and possibilities. In doing so, it not only documents existing work but also provides a foundation for further inquiry, guiding both research and practice.

By integrating livingness, design extends the possibilities of materiality, creating artefacts that evolve, adapt, and interact – offering new opportunities for sustainable innovation and cross-disciplinary research.

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3. Design natural matter for healthcare

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ABSTRACT

This chapter examines how natural matter can be integrated into the design process to create holistic solutions applied to the healthcare field. Framed within the context of livingness, it analyses the transformative potential of living systems such as bacteria and yeasts in re-framing how healthcare is designed. With an emphasis on the human microbiome as a catalyst for design exploration, it investigates microbial ecosystems such as the gut, skin, and vaginal microbiomes to underscore the critical role of these communities in reshaping our notion of physical, mental, and emotional well-being, illustrating how microbiome-driven design strategies inspire symbiotic solutions and promote deeper ecological awareness. Following a broader overview of the future applications of living systems in the medical field – from synthetic biology used in diagnostics to bioprinting living and responsive scaffolds for regenerative medicine – the chapter concludes by addressing challenges in scalability and cultural acceptance and proposing approaches for their implementation.

3.1 Design for healthcare

The 2030 Agenda for Sustainable Development, which was embraced by all UN members in 2015, offers a framework for advancing peace and prosperity for people and the planet in the present and the future. The most recent United Nations report addressing *Good Health and Well-Being* (2024) analyses how progress has slowed in important areas like access to necessary healthcare, maternal mortality, and early deaths from serious non-communicable diseases, highlighting how the climate crisis makes already existing disparities worse, especially for vulnerable groups. As climate change accelerates, exacerbating social inequalities and threatening ecosystems worldwide, design offers a powerful framework for developing sustainable, adaptive, and systemic solutions (Manzini, 2015). Design disciplines have progressively been adopted as a method of problem-solving and are recognised as a means of holistically unpacking complex problems and conceptualising solutions to address the needs of all stakeholders. Traditionally, design in healthcare has come in many shapes and forms, with design methodologies being used to explore a range of products, technologies, services, processes, and systems, considering both design and health as fundamentally human-centred and outcome-driven (Nusem, 2018). The idea of *Human-Centred Design* (HCD) describes a method of designing and developing systems that places the needs, actions, and experiences of users first, incorporating usability concepts to improve efficacy. Research shows that HCD is widely employed across medical disciplines, with many professionals applying it to develop person-centred healthcare solutions (Göttgens & Oertelt-Prigione, 2021).

3.2 Integration of natural matter

While HCD has contributed to a deeper understanding of human needs and values, its inherently humanist perspective – often assuming users to be white, male, and able-bodied – has unintentionally excluded diverse human and nonhuman perspectives (Braidotti, 2013). Increasingly, anthropocentric design approaches are being recognised as insufficient in addressing contemporary challenges, necessitating new methodologies to foster more sustainable and inclusive futures (Tironi *et al*., 2023). In response, many design researchers are shifting away from HCD paradigms toward more-than-human approaches. This perspective challenges human exceptionalism and embraces a relational framework, recognizing that humans, nonhumans, and the environment are intrinsically interconnected and can only be understood in relation to one another. In the realm of more-than-human design, integrating diverse life forms into the design process has become a fundamental part of biodesign. The concept of livingness within natural matter adds a dynamic dimension to the design process, where design outcomes are not static but grow, decay and interact with their surroundings (Karana *et al*., 2020). In healthcare, this includes self-regenerating materials, bio-sensors, bio-actuators, and bio-based scaffolds embedded with microbial consortia, which respond to changes, enabling bio-responsive and adaptive solutions.

3.3 The microbial scale

Microbes – an umbrella term for bacteria, archaea, protists, fungi, and viruses – are typically microscopic, averaging around one micrometre in size. According to the microbiologist Dr Drain (2017), microbes such as yeast, bacteria, and moulds have been used by humans for over 7,000 years for brewing, baking, and producing dairy products, and, in the last century, for creating chemicals like citric acid, amino acids, and pharmaceuticals. Many researchers such Dr Marsh *et al.* (2014) explain that, during periods when water contamination posed significant health risks, populations often favoured fermented beverages over water due to the fermentation process, which not only enhanced the safety of these drinks by reducing pathogen presence but also contributed to their health-promoting properties. A more recent example is Alexander Fleming's 1928 discovery of penicillin, resulting from the mould contamination of Penicillium notatum, which inhibited Staphylococcus growth. This chance observation led to the development of antibiotics, revolutionising medicine and saving millions of lives. Today, we understand that ecosystems of microbes inhabit not only our bodies (the human microbiome) but also the environments we live in (the microbiome of the built environment), intersecting with the microbial communities in urban areas (the urban microbiome) (Armstrong, 2022). Armstrong argues that understanding these interconnected microbiomes at different scales not only reveals hidden biological networks but also opens up new possibilities for design interventions that engage with living systems, from microscopic to macroscopic scales.

3.4 The human microbiome

The following paragraphs will explore the human microbiome as a significant area of interest for incorporating living matter, particularly microbes, into healthcare design. The human microbiome, which plays a crucial role in overall health, includes various microbial communities within our bodies, such as bacteria and yeast, which thrive and respond dynamically to our daily activities, including sweating and eating. These paragraphs will focus on three key human microbiomes – the gut, vaginal, and skin microbiomes – examining their roles in health and potential applications in biodesign.

Figure 1.
The Scatalog by Alexandra Daisy Ginsberg and James King. Photography by Louise Hagger. Styling by Olivia Bennett. Photo Credits from the authors of the projects.

3.4.1 Gut microbiome

The microbiologist Giulia Enders (2018), an expert in the gut, argues that while scientific research has traditionally concentrated on the human-scale world, contemporary studies are increasingly shifting their focus toward the microbial realm, with the gut microbiome emerging as one of the most intricate and least-understood biological frontiers. The gut microbiome comprises approximately 99% of the body's total microbial population and plays a fundamental role in digestion, vitamin production, and immune system regulation. At birth, infants acquire their gut flora primarily from their mothers through vaginal delivery and breastfeeding, which provides essential support for digestion and immunity, emphasising that these early microbial communities are crucial in shaping metabolism and overall health. By the age of three, the gut microbiota reaches a level of maturity influenced by diet, lifestyle, and environmental factors. Throughout life, the microbiome continuously adapts to stress, illness, and ageing, forming a unique bacterial fingerprint that significantly impacts an individual's health. However, microbial imbalances can contribute to conditions such as obesity, depression, and digestive disorders. Despite scientific advancements, researchers are still striving to fully grasp the complexities of these microbial interactions, often focusing on entire bacterial families or lineages to uncover their role in human well-being.

A remarkable provocation focused on the gut microbiome is the E. chromi Scatalog (Ginsberg, 2009), a speculative design project presented at the iGEM competition by Alexandra Daisy Ginsberg and James King in collaboration with Cambridge University students. It envisioned a future (set in 2039) where engineered bacteria in probiotic yoghurt could detect diseases in the gut, producing colour-coded faeces as a diagnostic tool (Figure 1). The project explored synthetic biology's potential beyond its typical machine-inspired imagery, emphasizing the biological and aesthetic challenges of designing with living materials. However, eight years on, Daisy Ginsberg (2017) questions the ethical, cultural, and technical implications of engineering living organisms, highlighting concerns about stability, self-diagnosis, and synthetic biology in healthcare. She argues that the rise of companies using engineered microbes for diagnosis raises issues of ownership and surveillance, while the microbiome remains a complex challenge for designers and scientists.

3.4.2 Vaginal microbiome

The vaginal microbiome is a dynamic ecosystem predominantly composed of bacterial communities, with Lactobacillus species playing a crucial role in maintaining vaginal health. These bacteria produce lactic acid, which lowers vaginal pH, thereby preventing the overgrowth of pathogenic microorganisms. Disruptions in this balance, known as dysbiosis, have been linked to various adverse health outcomes, including bacterial vaginosis, increased susceptibility to sexually transmitted infections, and complications in pregnancy. Factors influencing the composition of the vaginal microbiota include daily habits, lifestyle choices, and hormonal changes, all of which can impact vaginal health. Interesting is the contribution from Dr Emily Wissel (2021) who challenges the mainstream discourse around vaginas, which often revolves around stigma, sexual politics, and unnecessary products that harm vaginal health. She explains the complex microbial interactions within the vagina, emphasising how chronic stress – often caused by systemic inequalities – affects glycogen levels and, in turn, microbial balance. Wissel critiques the biomedical model for fixating on Lactobacillus as the sole marker of health, ignoring the validity of non-Lactobacillus microbiomes. This evidence highlights how vaginal microbiome research is biased toward cis-gendered white women, pathologising diverse but healthy microbiomes found in Black, Latina, and gender-diverse individuals. Consequently, a more inclusive understanding of vaginal health should recognise the diversity of microbial ecosystems that support well-being beyond narrow biomedical definitions.

In alignment with this, the author's speculative project The Soothing Cup (Bishop, 2022) explores the relationship between the menstrual cycle and the vaginal microbiome, challenging the cultural stigma surrounding menstruation and vaginal health. By focusing on the vaginal microbiome's role in preventing infections, restoring balance, and alleviating symptoms like dysmenorrhea, The Soothing Cup offers an alternative to traditional single-use menstrual products. The project introduces a bio-based menstrual cup that can host the growth of healing microorganisms naturally occurring in the user's vaginal microbiome, alongside an incubator that mimics the vaginal environment, allowing people who menstruate to grow their microbes a few days before menses begins (Figure 2). This process promotes self-care and knowledge about menstruation and vaginal microbial communities while challenging societal taboos and creating a healthier, more intimate connection with the body.

Figure 2. The Soothing Cup by Lucrezia Alessandroni. Photography by Paul Cochrane. Photo Credits from the authors of the projects.

3.4.3 Skin microbiome

The skin microbiome is composed of billions of microorganisms, including bacteria, fungi, protists, and viruses, that inhabit distinct skin niches – sebaceous, moist, and dry. Despite the skin's acidic pH, low moisture, and antimicrobial molecules, microbial diversity thrives due to these microenvironments, which shape the composition of resident communities. These microorganisms play a fundamental role in maintaining skin health by forming a protective barrier against pathogens, regulating inflammation, and supporting immune function. However, modern hygiene habits, excessive cleanliness, and urban lifestyles have disrupted this delicate balance, reducing microbial diversity and contributing to conditions such as eczema, atopic dermatitis, acne, and dandruff. The 'hygiene hypothesis' suggests limited microbial exposure weakens immune development, making individuals more susceptible to allergies and inflammatory skin disorders (Cingi

& Muluk, 2017). The current research underscores the importance of microbial diversity in promoting a resilient skin ecosystem, emphasizing the need to reassess hygiene practices and environmental factors that shape the skin's microecology (Moissl-Eichinger *et al.*, 2018).

An interesting application is Rosie Broadhead's SKIN SERIES™ which explores the relationship between clothing and the skin, developing textiles embedded with bioactive ingredients that offer therapeutic benefits (Broadhead *et al.*, 2021). This project envisions a future where garments actively contribute to skin health by improving its immune system, encouraging cell renewal, and providing antioxidant and anti-inflammatory properties. Broadhead's research highlights the body's intimate relationship with materials, emphasizing skin as a permeable interface between self and environment. In

Figure 3.
The SKIN SERIES™ by Rosie Broadhead. Photography by Carla Rossi. Make-up by Yulya Zalesskaya. Hair by Catalina Sartor. Model Isis Lenos. Photo Credits from the authors of the projects.

collaboration with microbiologist Dr Chris Callewaert, SKIN SERIES™ investigates how encapsulated probiotic bacteria in textile fibres can enhance the skin microbiome (Figure 3). These beneficial microbes activate upon contact with skin moisture, effectively reducing body odour without the need for biocidal agents. This innovative approach challenges conventional textile treatments, proposing a shift toward symbiotic clothing that works with, rather than against, the body's natural microbial ecosystem.

3.5 Collateral technologies

Two technologies previously mentioned – synthetic biology and bio-printing – are often highlighted by the scientific community for their potential to revolutionise healthcare design. Synthetic biology is an interdisciplinary field that applies engineering principles to biological systems, enabling the creation of novel functions expressed by edited organisms. In the healthcare sector, synthetic biology has led to significant advancements, including genetically modified bacteria utilised to produce essential pharmaceuticals. Complementarily, biofabrication involves building with living cells – either engineered or not – and biological materials (such as hydrogel to develop scaffolds), usually applied in tissue engineering and regenerative medicine.

However, many of these technologies raise both ethical and scalability issues, making it difficult to move from a lab-scale to an industrial scale. In an interview with the Design Museum in London, during the Waste Age exhibition, the biodesigner founder of Faber Future Chieza (2021), emphasizes that scaling should be viewed in a more distributed, localized manner, drawing inspiration from how nature manages scalability. Furthermore, she points out that the prevailing mindset of endless growth and disregard for planetary boundaries must be re-evaluated, arguing that addressing climate change requires a shift in consumption patterns, as the throwaway culture is incompatible with biological fabrication. Without this shift, scaling efforts could become a form of greenwashing rather than genuine environmental change.

3.6 Conclusion

This chapter has explored the integration of natural matter, particularly microbial life, into healthcare design, illustrating its potential to foster more sustainable, adaptive, and biologically attuned innovations. Moving beyond traditional human-centric approaches, it examined the vital role of microbial ecosystems – such as those within the gut, skin, and vaginal microbiomes – in shaping health and well-being. The discussion also highlighted how biodesign, synthetic biology and biofabrication are opening new possibilities for responsive, regenerative, and symbiotic healthcare solutions.

However, several challenges must be addressed. Beyond issues of scalability, ethical considerations, and societal acceptance, a major hurdle lies in the sheer complexity of interconnected living systems and ecosystems across all scales. Designing with biological materials requires an understanding of dynamic, interdependent relationships that extend from the microbial to the planetary level. To navigate this complexity, deeper interdisciplinary collaboration is essential – bridging design, science, healthcare, and policy to develop holistic, context-sensitive, and ecologically responsible healthcare solutions. By embracing these interconnections, we can move toward a future where healthcare design is not only human-centred but also deeply integrated with the living world.

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4. Living textile ecosystems: exploring three future scenarios of livingness at the intersection of biodesign and fashion

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ABSTRACT

The fashion industry's impact has reached a critical point, with the increasing textile waste and fast fashion at the core of unsustainable production-consumption cycles. Addressing the urgent need for circular and regenerative solutions in design materials and processes, this chapter delves into the transformative potential of integrating biological organisms into fashion, envisioning textiles as dynamic ecosystems. Drawing from six pioneering case studies, the authors propose and reflect on three future scenarios leveraging livingness in design to create a low-impact system. *Bio-loop* garments emphasise biodegradability and regeneration, *symbiotic fashion* concepts foster cooperative connections, and *living skins* integrate responsive and adaptive textiles to enhance health and functionality. These speculative approaches reimagine the future of fashion as restorative, emotional, and interactive, promoting a co-evolving relationship among wearers and garments.

4.1 The need to enter in a new era

The fashion industry, along with the textile industry, is undergoing a profound transformation, particularly given its considerable global impact (Mitchell, 2024; Sadowski *et al.*, 2021). Statistical evidence indicates that the fashion sector is of significant economic importance, representing the fourth largest business worldwide (Vilaça, 2021). Notwithstanding the deleterious hurdles on its supply chains due to the COVID-19 pandemic and social justice issues (Buchel *et al.*, 2022), this system is dynamically expanding. Indeed, its value is growing, and the total fiber demand is expected to reach 142 million tons in 2030 (Gschwandtner, 2022). Along with production, consumption is increasing, exacerbated by the spread of the fast fashion phenomenon (Candido, 2021).

Lately, the fashion sector has attracted widespread attention, having emerged as a prominent driver to a multitude of disasters, with ecological exhaustion being a prominent concern (Niinimäki *et al.*, 2020). The industry has been identified as a substantial contributor to greenhouse gas emissions, water pollution, biodiversity depletion, and waste production (Brydges, 2021; Musova *et al.*, 2021). In addition, albeit hundreds of international standards and trade unions have been introduced, the fashion industry is still blameable for low remuneration, discrimination based on gender and race, violence, child labour, unsafe and dangerous working conditions and lack of respect for their human rights (Fashion Revolution, 2020). The inherent risk associated with these unsustainable practices stems from the utilisation of a linear *take-make-waste* model (Ellen MacArthur Foundation, 2017).

Despite the evident necessity for systemic change to embrace sustainable development, a persistent struggle to transition persists. A significant challenge arises from the necessity to adopt the perspective that all materials have a finite origin. This standpoint contrasts with previous assumptions that materials are «provided free of charge by nature» (Acaroglu, 2018), suggesting the recognition of the prominent state of material depletion. In this context, the integration of circular economy models, or even more advanced regenerative models, has the potential to decrease both the existing waste and the latest environmental impact of the fashion industry (Ellen MacArthur Foundation, 2020, 2022). This requires a holistic view of the products' life cycles (Cole, 2012) and involves strategies like recycling, rethinking, reusing, and reducing at all stages of the supply chain (Brydges, 2021). Designers play a crucial role in the shift to circular fashion (Dutt & Gandhi, 2024), being the key agents of change and exerting a direct influence on economic, environmental, and social structures through creativity and innovation (World Design Summit Organization, 2017).

Buchel *et al.* (2022) recognise four *emerging fashion niches* as strategies addressing unethical and unsustainable fashion practices: technology and fibers, business models, value-chain models, and consumer awareness. New technologies like 3D printing and Life Cycle Assessment may enhance resource efficiency (McQuillan, 2020; Pollini & Rognoli, 2024; Sandvik & Stubbs, 2019), while collaboration among stakeholders could foster development in circular economy models (Hellström & Olsson, 2024). Fashion designers can also unlock circular principles with the potential to prolong or rethink the lifecycle of the products (Earley & Goldsworthy, 2015). This may be achieved by incorporating recycled, bio-based or living materials, along with the promotion of consumer education on circularity through their products (De los Rios & Charnley, 2017; Dragomir & Dumitru, 2022; Musova *et al.*, 2021).

This chapter aims to educate and trigger fashion designers to adopt innovative strategies for integrating circular practices into their work. Specifically, it explores the intersection of fashion and biodesign, highlighting the transformative potential of incorporating living organisms into textiles for approaching regenerative futures. Through an analysis of pioneering and speculative case studies, the authors present three key future scenarios for the fashion system, critically examining both the opportunities and challenges associated with livingness in the design development of garments.

4.2 Growing the future of fashion

The convergence of biology and biotechnology with design fields represents an optimal paradigm shift in how products are conceived, produced, and consumed. These transitional circular conceptions offer plentiful advantages for finding alternatives to the current system. However, adopting a circular economy model in the design and fashion industry represents a vast and complicated attempt.

Several approaches rethink the existent linear system and support the possibility of combining nature and biology with design purposes (Camere & Karana, 2017). Going beyond the notions of biophilia (Wilson, 1984) and biomimicry (Benyus, 1997), this chapter focuses specifically on the application of biodesign in materials experimentation, intending to address the issue of material extraction in the life cycle of fashion products. Indeed, biodesign proves to influence the sustainable transition at a sources level (Keune, 2021), paving the way for regenerative futures (Karana *et al*., 2023). This biological approach to design – incorporating «living materials into structures, objects and tools» (Myers, 2012, p.8) – guides practitioners to envision a perspective in which new materials could be obtained not only from traditional resources but also from unusual, wasted and renewable assets (Duarte Poblete *et al*., 2024). Positioning «nature as a co-worker» (Collet, 2013), this «design with the product of biology» (Biofabricate & Fashion for Good, 2020) integrates living organisms as crucial components that could improve the function of the final product. The potential of biofabricating materials is, therefore, delineated by the transition from inanimate matter to substances that are alive or co-designed with biological organisms.

The incorporation of livingness proves to be an obvious opportunity for the fashion world, as the principles of biodesign can contrast the typical aspects of fast fashion. Firstly, the industry is characterised by rapid and intensive production cycles, with new collections being released every few weeks. In contrast, biodesign utilises living materials and natural processes, which necessitate longer growth and incubation, promoting slower, more thoughtful production timelines (Collet, 2021a). Additionally, the fast fashion paradigm is heavily reliant on synthetic materials to reduce costs and enhance durability.

Conversely, the use of natural and even living materials in design is often associated with higher production and processing costs, demanding that consumers embrace more judicious or deliberate consumption patterns. The current fashion model is designed to be consumed *fastly* and then discarded, thus incentivising a culture of disposal, whereas the design of livingness promotes artefacts that require care and can even regenerate. Furthermore, the fast fashion industry relies on large-scale production of identical garments. In contrast, biodesign offers tailored and customised solutions based on materials that can adapt to the body or undergo change over time. Lastly, as previously mentioned, fast fashion is among the most polluting industries, with CO_2 emissions, water waste and resource exploitation. Within this context, biodesign can provide a range of more circular materials, with a focus on intrinsically carbon-negative solutions (Toussaint *et al*., 2024).

A key advantage of biodesign is its versatility to integrate living organisms such as fungi, bacteria, algae and plants (Camere & Karana, 2017, 2018) into viable alternative textiles, as niche fashion pieces and accessories (Rognoli *et al*., 2022). Beyond their aesthetic and environmental benefits, living materials enable new functional properties, including garments that self-repair, adapt to environmental conditions, or naturally decompose at the end of their lifecycles (Antonelli, 2020).

By embracing living materials, circular economy principles and interdisciplinarity, fashion can evolve into a low-impact system where materials are biofabricated and grown. In this context, the convergence of design, science, and technology becomes essential to drive the future of fashion, ensuring that regenerative development represents the foundation of the industry.

4.3 A look into the real-world case studies in living fashion

It is widely acknowledged that the fashion industry demands a radical rethinking of production and consumption models due to its environmental and social consequences. The emphasis has shifted from merely developing sustainable or circular materials to redefining the very role of fashion on our planet. It is erroneous to consider fashion as a closed system, given its intricate interconnection with multiple sectors, including agriculture, chemistry, technology and communication. Furthermore, the consumption of clothing is no longer solely linked to *possession*; instead, it is increasingly associated with the experience it offers, the interactions it fosters, and the meanings it conveys (Conti & Franzo, 2024).

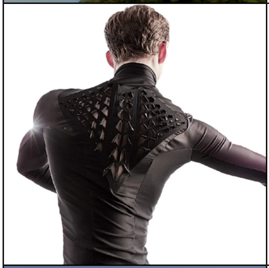
This perspective paves the way for the introduction of living organisms into the sector, moving beyond anthropocentrism and embracing a *more-than-human* approach (Tarcan *et al*., 2022). As Smelik (2022) observes, posthuman fashion does not merely envision an immaterial future but actively explores «the interconnections across species, cultures, categories and concepts, undoing binary oppositions between humans and non-humans» (p.7). The concept of *designing with* living organisms (Tomico *et al*., 2023) in fashion transcends mere product creation, encouraging a deeper, symbiotic collaboration with natural systems rather than their exploitation (Toussaint *et al*., 2024). The application of biodesign principles within the disciplines of fashion and textile design redefines the life cycle of traditional garments, entailing livingness as a material quality encompassing the ability to grow, mutate, and interact with their surroundings (Karana *et al*., 2020). While conventional fashion design products prioritise durability and permanence, biodesign embraces concepts like short life, ephemerality and imperfection as valuable characteristics rather than limitations (Parisi & Shetty, 2020).

In the domain of bio-based materials in sustainable textile and fashion design, D'Itria and Colombi (2022) identified three overarching themes: innovative design, biofabrication and emotional design. The first theme involves developing new technologies to create biobased materials, exemplified by Orange Fiber, a startup that extracts and spins cellulose from citrus juice by-products. The second theme, biofabrication, focuses on refining existing systems to integrate biobased materials into the circular economy, as seen in Seacell (SmartFiber AG). Lastly, emotional design explores the sensory and experiential qualities of materials (Giaccardi & Karana, 2015; Karana *et al*., 2015), fostering attachment and empathy in products.

Drawing upon this exemplary framework, the authors propose the exploration of six pioneering and speculative case studies that intersect biodesign with the fields of fashion and textile design (summarised in Table 1). The objective is to define the potential and the challenges underlying this interdisciplinary hybridisation.

The six case studies analysed reveal a fundamental paradigm shift in fashion, where textiles evolve from inert materials into active, living entities. The intersection of fashion design and biodesign opens the

Table 1. Analysis of the 6 case studies. Photo Credits from the authors of the projects.

Case Study Image	**Project Title & Designer(s)**	**Description**
	**Physarum Lab & BLACK WALNUT AS24+** *Piero D'Angelo* https://www.pierodangelo design.com/	The designer's work explores the biophilic aesthetics and intelligence of biological organisms in fashion design to challenge the conventional role of textiles. *Physarum Lab* investigates the behaviour of *Physarum polycephalum*, a slime mould capable of complex problem-solving, using its movement patterns to influence design structures. The capacity of bacterial pigment dyes to colour clothing and absorb CO_2 is highlighted in another collection, *BLACK WALNUT AS24+*, which was created in partnership with textile artist Belinda Budge. It also integrates lichens, transforming garments into self-regulating and ecologically responsive elements.
	**bioLogic** *Tangible Media Group* https://tangible.media.mit.edu/ project/biologic/	Developed by MIT's Tangible Media Group, *bioLogic* is an interactive textile project that integrates *Bacillus subtilis* bacteria into fabric to create garments that respond to the wearer's body temperature and sweat. The bacteria react to humidity and heat by expanding and contracting, enabling the fabric to self-ventilate when the body overheats, as a biological second skin. By shifting away from passive materials toward dynamic and responsive clothing, this project demonstrates the potential of microorganisms to generate novel functionalities and symbiotic relationships with humans.
	**Melwear** *Maca Barrera* https://www.gpaward.com/en/ produkte/melwear	*Melwear* introduces a pioneering approach to UV protection in fashion by mimicking melanin, the natural pigment found in human skin that protects against UV radiation. By embedding a membrane of bacterial melanin into textiles, the project merges biotechnology and fashion, envisioning clothing as an extension of the body's protective systems. This innovation signals a shift toward functional, biologically enhanced fabrics, where garments go beyond covering the body through functionalities as interacting, shielding and adapting.
	**Biogarmentry** *Roya Aghighi* https://www.dezeen. com/2019/10/02/ biogarmentry-roya-aghighi- living-clothes-photosynthesis/	Roya Aghighi's *Biogarmentry* collection takes the fashion industry to a new level by introducing living textiles that entail photosynthesis. The fibres are biofabricated with algae, allowing the resulting garments to absorb CO_2 and release oxygen just like plants. Beyond conventional clothing, *Biogarmentry* pieces require care since they must be watered and exposed to sunlight. Instead of treating clothing as disposable, this project encourages wearers to nurture their garments, turning the act of wearing into a deeper, collaborative, symbiotic relationship between fashion, environment, and humans.

	**O°** *Oxman* https://oxman.com/projects/o0	Oxman team's *O°* project consists of programmable disposable shoes, pushing the boundaries of posthuman design. This groundbreaking work is entirely composed of polyhydroxyalkanoates (PHAs), a polymer produced through the utilisation of engineered microorganisms. Employing diverse digital manufacturing techniques, such as 3D printing, hot melt spinning and knitting, the concept envisions fashion shoes that contribute to the preservation of natural systems. The project also exemplifies the integration of interdisciplinary expertise, merging professional figures coming from synthetic biology, green chemistry, materials engineering, design, and computation.
	**LOEWE SS23** *Loewe x Paula Ulargui Escalona* https://paulaularguiescalona.com/LOEWE-SS23	The Spring/Summer 2023 collection by Loewe Paris, in collaboration with the designer Paula Ulargui Escalona, introduces sneakers and garments integrating growing plants. Escalona's expertise in biotextiles led to the development of living pieces of clothing infused with living plants, where grasses and other seedlings were cultivated within the fabric itself. This approach blends botanical studies and textile design, shifting fashion toward a regenerative, living ecosystem where the wearer can feel a part of nature.

way to reshaping the industry by creating garments that breathe, evolve, grow, adapt and interact with their environment. These pioneering projects intertwine matter, technology, and livingness, offering a glimpse into the future of regenerative fashion.

4.4 Three scenarios at the intersection of biodesign and fashion

The speculative case studies explored provide a valuable exemplification of the potential of material innovation and a new paradigm for understanding fashion design, ranging from bacterial membranes to algae-based textiles cultivated in direct interaction with the human body. Through livingness, the fashion industry can embark on the transition from a culture of extraction and waste to one of regeneration, symbiosis and intelligence.

At the core of the perspective grasped through these innovative examples, three key future scenarios leveraging living organisms in fashion design are envisioned (Figure 1) and proposed as follows.

4.4.1 Bio-loop fashion: from nature back to nature

The future could bring both daily and luxury fashion as a biological experience, where growing, evolving, and ephemeral materials

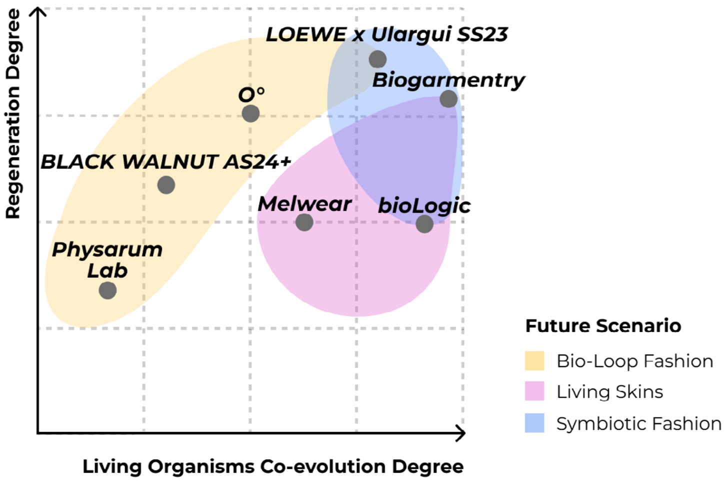


Figure 1. Positioning of case studies and three speculative future scenarios at the intersection of Fashion Design and Biodesign. *The vertical axis represents the ecological performance of design strategies, expressed through a Regenerative Degree, while the horizontal axis illustrates the extent of co-evolution between living organisms and garments' wearers, highlighting the integration of biological systems in relation to both functionality and mutual adaptation.*

become the ultimate expression of exclusivity, customization and sustainability. High fashion, for example, can be potentially redefined through living materials, as seen in *LOEWE SS23* or *O°* (Oxman). By embedding biologically and aesthetically pleasing organisms such as plants, lichens, algae, and moss in garments, designers can promote concepts of restoration, biodegradability, and reduced environmental impact. *Bio-loop Fashion* mirrors natural, short life cycles, resulting in haute couture and trendy pieces designed to grow, evolve, be worn a few times, decay and then return to nature. This closed-loop scenario could set a precedent for regenerative systems that embody low-impact practices, driving the industry toward a truly circular economy.

4.4.2 Symbiotic fashion: garments as living systems

Instead of passive consumption, fashion may shift toward artefacts that activate care-based and symbiotic interactions, forming a co-dependent and cooperative relationship between wearer and garments. This is evident in *Biogarmentry* (Roya Aghighi), where fabrics infused with algae must be nurtured, watered and exposed to sunlight to remain alive. In this scenario, fashion consumers become *gardeners* of their clothing (Mang & Reed, 2013), fostering an emotional, caring bond with their garments. The fashion pieces, in turn, can become living companions with functional and dynamic components – such as organisms that purify air, change color, or assist in biodegradation. These materials seek to establish a new consumption model of circularity where garments are appreciated and maintained like living entities. Thus, this approach aims to educate consumers and alter their relationships with fashion by perceiving garments as *difficult-to-dispose* products and preventing landfill waste.

4.4.3 Living skins: bio-responsive and adaptive clothing

Inspired by *Melwear* (Maca Barrera) and *bioLogic* (MIT Tangible Media Lab), this scenario imagines clothing that not only adorns the body but enhances personal well-being and comfort. Through the intersection with biotechnology, fashion design moves beyond static materials and leads to the creation of responsive garments integrating biological actuators, able to adapt in real time to environmental conditions and physiological needs. *Living skins* are pieces augmented by the remarkable and intelligent functionalities of living organisms, such as responding to conditions like UV exposure and pollutants or even self-cleaning over time. The potential applications of these wearable systems are diverse: they could hydrate the skin, provide antimicrobial protection, shield against pollutants, and enhance mood through scent-based compounds. Additionally, they could be designed to extend garment longevity and minimise waste by reducing the need for frequent washing, thereby lowering pollution and offering novel interactive experiences for the wearer.

The presented future fashion scenarios must not be considered as mutually exclusive. They create a complex and layered landscape in which different trends and functionalities could coexist. Fashion could become more organic, interactive, and responsible, but also more ephemeral, smart and fluid. These scenarios represent a radical transformation of the fashion paradigm from an industrial approach, based on mass production and the use of inert materials, to an organic, symbiotic and interactive vision. They mirror contemporary challenges such as the environmental crisis, the redefinition of the relationship with technology and the search for new consumption patterns. Therefore, they suggest that the fashion of the future will no longer be represented solely by aesthetic or social expressions. Instead, it will be embodied by living ecosystems that evolve with the wearer and the planet.

4.5 Future challenges & open discussions

The most important change that is taking place in the fashion industry is the transition from a linear to a circular supply chain. Scientific research can also accompany the world of fashion in the challenge that all brands have in common: the development of more environmentally sustainable fabrics. While the textile industry initially used mainly virgin fibres, there is now a growing trend to use new-generation yarns, often made with regenerated materials or recovered from waste and scraps. It is clear, therefore, that research constitutes a fundamental contribution in the innovation process within this sector. The integration of biodesign into fashion design presents several challenges that need to be addressed to enable widespread adoption and industrial feasibility. A number of obstacles to this shift have been identified and are listed below:

- the propensity of companies to include experts, such as designers, engineers and biotechnologists, in their fields of operation (Quijano *et al*., 2024);
- scalability and automation, which pose significant concerns, especially because current methods are not yet optimised for large scale, limiting their accessibility in commercial fashion (Abdelmeguid *et al*., 2024);
- costs, as biobased and biofabricated materials are still significantly more expensive than traditional textiles, which also requires progress in material standardisation (Voukkali *et al*., 2024);
- durability and performance, since many biofabricated textiles have yet to meet industry requirements in terms of wear resistance, longevity and washability (Williams & Collet, 2021);
- education and acceptance of companies and consumers who are unfamiliar with bio-based products and may hesitate to adopt garments made from living materials due to concerns about comfort, hygiene and maintenance (Quijano *et al*., 2024);
- ethical implications and debates on the manipulation of living entities for fashion purposes (Collet, 2021b).

Beyond these challenges, the future of fashion will undoubtedly benefit from livingness, giving birth to a revival of dynamism made of *vibrant matter* (Bennett, 2010). By minimising waste, eliminating toxic chemicals, and enabling compostable or regenerative products, designing with living materials presents a transformative opportunity for fashion design. It could represent the key to move away from fossil fuel–based materials and significantly reduce the fashion industry's carbon footprint.

As evidenced through the case studies, the integration of biodesign into fashion is already transitioning from an experimental phase to real-world applications, signalling a fundamental shift in the systems. Biofabricated materials such as bacterial membranes, growing shoes or algae-based fibres are emerging as viable alternatives to conventional textiles, offering sustainable and regenerative solutions that align with the principles of a circular economy.

Whilst the development of these products for market release still seems a significant way off, the proposed future fashion scenarios call for rethinking not only the garments themselves but also how we experience our clothes. In a reality where clothes can breathe, interact, and grow, these living textile ecosystems will redefine the boundaries of fashion, fostering a future of regeneration, symbiosis and co-evolution.

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PART 2

Exploring livingness in practice

5. Living materials for yacht design

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ABSTRACT

The yachting industry increasingly reflects the evolving values and lifestyles of its owners, creating an opportunity for design to redefine onboard experiences through holistic and emotionally engaging solutions. This shift is particularly relevant considering the growing environmental concerns, emphasizing the urge to integrate sustainable materials. This chapter explores a speculative and interdisciplinary design approach to nautical environments by envisioning living organisms as dynamic and regenerative design alternatives to conventional elements. Building on the outcomes of a professional workshop held in Milan and engaging Interior Yacht Design students, it explores how living artefacts can enhance design aesthetics, foster new interactions between spaces and users, and inspire immersive scenarios. The involved activities encourage critical reflection on the role of livingness in future yacht design, identifying its potential for sustainability and innovative functionalities.

5.1 The shift towards sustainability in yachting

The yachting industry is undergoing a profound transformation driven by sustainability imperatives, technological advancements, and evolving consumer expectations (Ansaloni *et al.*, 2024; Deloitte, 2024a; Deloitte, 2024b). Traditionally associated with luxury and exclusivity, yacht design is increasingly incorporating principles of eco-efficiency, circularity, and environmental responsibility.

Sustainability is no longer a secondary consideration but a defining element of contemporary yacht design, shaping both the aesthetic and functional dimensions of future vessels. This shift is reflected in the adoption of alternative propulsion systems, sustainable materials, and innovative design strategies that minimise environmental impact while enhancing onboard experiences (Piccioni *et al.*, 2024). Yacht shipyards are increasingly prioritizing sustainability through eco-friendly materials and cleaner technologies. Traditional materials such as fiberglass and carbon fibre composites are being replaced by bio-based alternatives, recycled metals, and low-impact coatings (Baley *et al.*, 2024; Ravasio, 2022). Simultaneously, advancements in propulsion and energy efficiency – such as hybrid systems and alternative fuels – are becoming standard industry practices (Carmosino *et al.*, 2021). A key example is the integration of green methanol fuel cells, as seen in models like the Sanlorenzo 50Steel.

Recent developments highlight a growing interest in biophilic and nature-inspired design approaches, rethinking spatial configurations to foster a closer connection with the marine environment (Pandey & Madan, 2024). Biophilic design seeks to restore the intrinsic bond between humans and nature within built environments, enhancing well-being, cognitive function, and sensory engagement and promoting psychological and physiological benefits. According to Kellert *et al.* (2008), it integrates both direct and indirect experiences of nature, utilising environmental features, natural materials, and spatial configurations that evoke organic patterns.

In yacht design, biophilic principles are shaping onboard experiences by maximising natural light, optimising airflow, and incorporating materials and forms that enhance a seamless relationship with the marine environment. Key examples are Oceanco's *NXT* and the *Biophilic Super Yacht* concept by 3deluxe, where biophilic design actively contributes to environmental consciousness and human-nature interaction, aligning with the industry's shift toward sustainable luxury.

Developed in collaboration with TANK Design Studio, Oceanco's NXT initiative employs a nature-centred approach and integrates organic forms, dynamic lighting, and materials in luxury yacht interiors, reflecting natural textures and patterns. The design creates spaces that stimulate creativity and well-being, balancing ocean-inspired elements with soft, flowing shapes. Additionally, different decks are designed with distinct *energy moods*, fostering an immersive onboard experience. By aligning interior spaces with the surrounding seascape, *Oceanco NXT* exemplifies how biophilic design can redefine comfort and exclusivity in yachting.

Figure 1. Oceanco NXT – Nature-Inspired Luxury; Biophilic Super Yacht. Photo Credits from the authors of the projects.

The Biophilic Super Yacht concept by 3deluxe (Figure 1) reinterprets the traditional yacht layout, incorporating open, light-filled environments with a greenhouse, communal lounges, and dedicated spaces for cultivating fresh produce. By integrating a natural ecosystem on board, the yacht becomes a *floating Garden of Eden*, shifting luxury from synthetic materials to a living, breathable environment. This approach enhances well-being while aligning with sustainable innovation through zero-emission technologies and self-sufficient food production.

In the field of material selection for yachting, a growing interest is drawn by alternative materials with natural, smart, connected and adaptive components. In this context, living materials represent a transformative opportunity, introducing an additional dimension of personalisation while fostering a deeper connection between humans and nature. Their integration into yacht interiors could present a novel way to enhance exclusivity while reinforcing sustainability, allowing materials to become responsive, regenerative, and actively engaged with the onboard experience.

Based on insights from a professional workshop in Milan, this chapter investigates how living artefacts enhance nautical appearance, foster novel interactions between spaces and users, and inspire speculative design scenarios. The interdisciplinary nature of the workshop encouraged critical reflection on *livingness* in yacht interiors, with an emphasis on sustainability, adaptability, and experiential integration. Furthermore, it examines the role of living materials in redefining yachts in aesthetic, functional, and environmental terms.

5.2 Approaching living organisms in yacht design

Customisation has always been a defining element of yacht design. Traditionally, this has been achieved through handcrafted materials, exclusive layouts, and high-end finishes, carefully selected to align with the yacht's intended experience (Ansaloni *et al.*, 2024). However, as sustainability and user experience gain prominence in the industry, the concept of customisation is evolving beyond aesthetics and craftsmanship to encompass dynamic, adaptive, and bio-integrated environments. Building on this evolution, the introduction of living materials could represent a paradigm shift, providing yacht design with an aesthetic that is both fascinating and innovative. This can involve engaging individuals on board with *novelty* dimensions such as trendiness, emotion, complexity and potency (Hsiao & Chen, 2006), which can be addressed through a new materialist perspective (Coole, 2013), as evidenced above by the biophilic trend. The smart and becoming nature of these materials (Bergström *et al.*, 2010) is recognized as a fundamental element in unlocking experiential levels (Karana *et al.*, 2020) of interaction and responsiveness.

On the other hand, living materials, as matter with an agency (Davies & Levin, 2023; Rosslenbroich *et al.*, 2024), can support the traditional functionality of products in yachts. Indeed, the living organisms integrated into them show intelligence through their ability of perceiving the external environment, being reactive, adapting, re-generating and renewing (Wang *et al.*, 2020; Peng *et al.*, 2023). Within design, living materials are shown to offer artefacts material qualities that enable them to sense, grow, evolve, and eventually decay (Karana *et al.*, 2020), yielding novel expressions and functionalities. Most of all, these characteristics can support regenerative futures and environmental sustainability (Karana *et al.*, 2023), resulting in minimal ecological footprints and innovative properties for the design of custom interiors. Among the many advantages are the enhancement of nautical spaces through improvements in energy efficiency, air and water quality, self-repairing structures, and the creation of interactive, bio-responsive environments.

Drawing inspiration from other design sectors, such as fashion and product design – which are currently embracing this speculative and fictional side of biological integration (Camere & Karana, 2018) – it is possible to derive different opportunities for yacht design. To demonstrate these potentialities, a 3-day workshop, entitled *Living Materials for Yacht Design*, was carried out within the Master of *Executive Interior Yacht Design* (EIYD) course at the PoliDesign (Politecnico di Milano, Italy). This approach enabled the rethinking of conventional design practices, whereby students in the field are typically expected to adhere to standard principles, offering livingness as a novel perspective for the field.

5.3 Workshop structure

The *Living Materials for Yacht Design* workshop was specifically designed as a speculative and interdisciplinary approach to verify how living artefacts foster novel interactions between spaces and users, provoking reflection and debate through hypothetical scenarios that challenge the conventions of traditional design.

The workshop, spanning 3 days, involved 19 Interior Yacht Design students hailing from diverse previous academic backgrounds, such as Product, Industrial, Interior, Nautical or Communication Design.

The activities followed the blueprint of the *Emerging Materials and Technologies* framework for design education and practice by Ferraro (2023), re-elaborating it through the specific incorporation of living materials. Particularly, the workshop was supported by the phases of *Understanding*, *Exploring*, and *Applying* (Figure 2).

- *Understanding* (4 hours + 4 extra hours). Before the launch of the workshop, a theoretical lecture on materials design and biodesign was delivered to the students to impart a foundation of knowledge on the subject matter. On day 1, students were provided with the fundamental understanding of biofabricated and living materials to comprehend the design brief in its entirety. In this stage, a renowned company from the Italian nautical sector collaborated with the teaching board, introducing participants to the key spatial configurations of boats, essential design strategies, and current market demands.
- *Exploring* (4 hours). The second step entailed the division of participants into 5 teams of 3 or 4 members. A toolkit containing 12 case study cards, each corresponding to the living organisms previously described, was provided to the students. The purpose of this toolkit was to guide the students in grasping the potential of livingness for specific design applications and interactions before starting the conceptualisation of innovative nautical interiors.
- *Applying* (12 hours). In this stage, the students were asked to integrate their concept ideas into speculative design scenarios. Each team was actively supported during this phase by professors, tutors and the company expert. All the drafted outputs of the previous phase (such as inspirational mood boards) have been refined according to the suggestions and the living organisms' features. The participants were finally asked to transform their project into a visual presentation, employing drawings and renderings and developing a compelling narrative.

Following the conclusion of the activities, the results were discussed among the participants. At this juncture, a questionnaire was proposed to students to assess their experiences and insights regarding the workshop and its underlying design process. The goal was to evaluate the effectiveness of the methodology phases, the relevance of the tools and activities used, and participants' prior knowledge and engagement with the concept of living materials in yacht design.

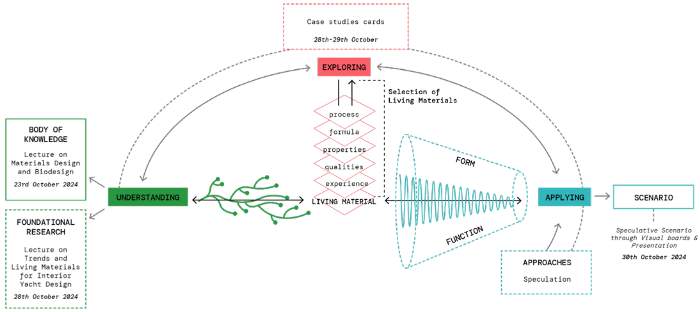


Figure 2. The framework of Understanding, Exploring and Applying stages (re-elaborated from Ferraro, 2023), along with the timeline of the workshop activities.

5.4 From classification to application: the living organisms involved in the design brief

During the *Understanding* stage, students were provided with the foundational knowledge on 4 main biological organism categories – *bacteria, eukaria, fungi, plantae* – ranging from ancestral prokaryotes to multicellular organisms. Within these, 9 specific living organisms were described, with a focus on their classification, specific needs, characteristic behaviours, key skills, limitations, design considerations, types of interaction, and agency in more-than-human design. Then, the introduction of 12 different case studies during the *Exploring* phase enabled participants to comprehend the potential sustainable applications of merging technology, biology, and design through the livingness. The following tables include the key workshop living organisms (summarised in Table 1) and the shared case studies (summarised in Table 2).

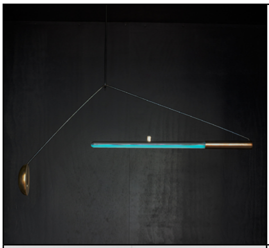
Table 1.
Overview of the living organisms illustrated during the workshop.

Biological organism	Description
Bacteria	
Escherichia Coli	A model organism in microbiology belonging to the *Proteobacteria phylum* and playing a crucial role in the human gut microbiome and biotechnology. In biodesign, it is highly regarded for its versatility and ease of genetic engineering. It is primarily used as a living sensor for detecting toxins, heavy metals, or other specific substances in the environment or within the human body (Belkin *et al*., 2017; Cheng *et al*., 2023; Mimee *et al*., 2018).
Vibrio fischeri	A bioluminescent marine bacterium that provides a natural, sustainable soft blue-green glow through a chemical process called *quorum sensing*, in which light production increases with cell density. Its applications range from conceptual bio-lighting installations to interactive displays that respond to environmental conditions, demonstrating the potential of microbial bioluminescence in reducing energy consumption and fostering a deeper connection between design and natural ecosystems (Cole, 2017; Tyse *et al*., 2022).
Geobacter sulfurreducens	A member of the *Deltaproteobacteria*, it is notable for its ability to reduce metal ions, making it valuable for bioremediation and bioelectrogenesis. Due to its conductive nanowires and metal-reducing abilities, *Geobacter* is used in bioelectronics, environmental cleanup, and renewable energy projects, functioning as a natural *bio-battery* to power minor electronic systems and contribute to eco-friendly solutions for pollution and energy challenges (Lovley *et al*., 2019).
Spirulina	Oxygenic photosynthetic cyanobacteria playing a critical role in converting CO_2 into oxygen. Their high growth rate, minimal resource requirements, and high nutritional value make them ideal for applications in biodesign. These applications range from developing biodegradable and living textiles to algae sensors to creating living architecture that addresses urban pollution challenges (Aghighi R., 2019; McCormick *et al*. 2011; Sawa *et al*. 2017).
Eukarya	
Pyrocystis fusiformis and *Lunula*	Two of the most commonly used organisms in biodesign, they are *Dinoflagellates*, known for their ability to produce bioluminescence when agitated. This quality can be utilized in design applications such as soft, evocative lighting for interiors, fashion, and even communication (Barati *et al*., 2021; Ofer *et al*., 2021; Van Dortmont, 2019).
Physarum polycephalum	A slime mould from the *Amoebozoa phylum* with remarkable problem-solving abilities and network optimization, making it a valuable model for studying emergent intelligence in non-neural systems. This organism plays a crucial role in interaction design, functioning as a biological computing interface capable of signalling environmental changes (Braund *et al*., 2016; Kahlke *et al*., 2016; Miranda *et al*., 2017).
Fungi	
Mycelium	The vegetative part of fungi forming an intricate network of *hyphae* that decompose organic matter and contribute to soil health. Mycelium also forms symbiotic relationships with plants, enhancing nutrient absorption through mycorrhizal associations. In biodesign, mycelium has multiple applications: it serves as a natural binder for agricultural waste to create renewable and biodegradable materials (Karana *et al*., 2018); it acts as a natural decomposer capable of digesting substances such as plastic waste, potentially transforming them into biodegradable materials (Arrowood, 2024); in experimental stages, it demonstrates the ability to produce electrical responses to different stimuli (Adamatzky, 2018).

Lichens	At the intersection of fungi and photosynthetic organisms, lichens emerge as a symbiotic organism composed of fungi and algae or cyanobacteria. In biodesign, lichens are valued for their ability to thrive in extreme conditions and efficiently absorb nutrients directly from the air, making them effective bioindicators of air quality. Their capacity to sequester pollutants and adapt to diverse substrates makes them ideal for eco-friendly installations, urban green walls, and sustainable architectural materials (Luz, 2024; Milner, 2023).
Plantae	
Bryophytes (living moss)	The ancient lineage of non-vascular plants, mosses play a crucial role in water retention, carbon sequestration, and ecosystem engineering, particularly in peatlands. In biodesign, living moss leverages its natural resilience, water-retention capabilities, and air-purifying properties to create sustainable, self-sustaining design elements in architecture, interiors, and products. This living material functions as a natural air filter, absorbing CO_2 and releasing oxygen, while its unique textures and colours introduce a lush, biophilic aesthetic. Unlike other plants, moss thrives in low-light conditions and requires minimal soil and maintenance, making it ideal for vertical gardens, green walls, and eco-friendly installations (Hong *et al.*, 2023; Meischke, 2023).

Table 2.
Overview of the 12 case studies proposed. Photo Credits from the authors of the projects.

Image	Project Title & Designer(s)	Main living organisms & functionality	Description
	**Bacterial Biocement** Laura Maria Gonzalez	*Geobacter* –Self-regenerating	This project uses bacteria to produce calcium carbonate, a substance that mimics the natural process of stone formation. The resulting biocement can regenerate itself by effectively repairing cracks.
	**Vespers III** Neri Oxman & the MIT Media Lab	*Escherichia Coli* – Colour-changing	*Vespers III* involves a bacteria species that can change colour in response to environmental stimuli like temperature or humidity. It merges bioengineering with design to create dynamic, responsive structures.
	**Glowpolis** Glowee	*Vibrio fischeri* – Bioluminescence	*Giowpolis* is the first experiment of bioluminescent urban lighting, launched in the city of Rambouillet, near Paris. The startup developed light tubes of liquid raw material containing billions of bacteria that emit a blue glow.

	**Ambio** Teresa Van Dongen	*Pyrocystis fusiformis and Lunula* – Bioluminescence	*Ambio* is a lamp that harnesses *dinoflagellates* in a seawater-like medium to produce a soft, natural light, oxygenating the microorganisms to trigger their light response.
	**Spark of Light** Teresa Van Dongen	*Geobacter* – Bioelectric energy production	This lamp produces light using electrochemically active bacteria, able to generate small electrical currents while purifying wastewater. This process requires a teaspoon of acetate and water on a biweekly and monthly basis, respectively, as nourishment in exchange for energy and light.
	**Electric Skin** Nada Elkharashi, Catherine Euale, Sequoia Fischer & Paige Perillat-Piratoine	*Geobacter* – Bioelectric energy production	This project employs a renewable, biodegradable and flexible energy source powered by *Geobacter*. It generates electricity through microbial electrochemical reactions, making it a promising alternative to traditional batteries.
	**Slime Mould Smartwatch** Jasmine Lu & Pedro Lopes	*Physarum polycephalum* – Bioelectric energy production	The slime mould integrated into this wearable can power it by converting its electrical signals into energy. The living circuit requires to be fed with oats and water, encouraging users to actively care for their technology.
	**Fungi Mutarium** Livin Studio & Utrecht University	*Mycelium* – Plastic digestion	The *Fungi Mutarium* project is an innovative food production concept using mycelium to digest plastic, converting it into a harmless form. This process offers a biological alternative to chemical degradation.
	**Gunya MYC_Couture 04** Atelier Dasha Tsapenko	*(Stabilised) Mycelium* – Thermoregulation	The garment was grown and biofabricated from raw compressed hemp and sawdust bound together with mycelium. Inspired by a typical Ukrainian mud hut named *mazanka*, it emulates its ability of thermoregulation.

	**H.O.R.T.U.S. XL** ecoLogicStudio & Synthetic Landscape Lab	*Spirulina* – Air purification	*H.O.R.T.U.S. XL* is an immersive installation of 3D printed structures embedded with spirulina that capture $C0_2$ and produce oxygen. Inspired by coral reefs, this *urban garden* prototype demonstrates the application of bio-digital technologies in architecture, integrating organic and digital processes.
	**Vertiscape** Respyre	*Moss* - Air purification, Thermoregulation, Water absorption, Pollutants filtration	The company incorporates moss into roof tiles and other building materials not only to enhance the aesthetic appeal of architecture but also to contribute to environmental sustainability. Moss naturally insulates the building and improves air quality by filtering pollutants and $C0_2$ and absorbing rainwater.
	**Grow your Own Couture** Piero D'Angelo	*Lichens* – Air purification	This speculative collection draws inspiration from biofabrication experiments conducted with the *Grow Your Own Couture DIY kit*, which enables the user to cultivate garments employing lichens. These living organisms are capable of absorbing air pollutants from the external environment.

5.5 Workshop results

Inspired by the dynamic interplay between biology and yacht design, the design process yielded five scenarios, which were translated and presented by the teams as visual and narrated representations of the selected living organism, yacht interior and envisioned concept. Among them, three projects explored the potential of light emission from different living organisms – *Elsa, SeaBed* and *AquaCelestia* – while the remaining two – *Ecosense and Spirulini* – focused on the sense of well-being, leveraging the capabilities of lichens, *Spirulina*, and *Physarum Polycephalum*.

Drawing inspiration from the Disney movie *Frozen*, the *Elsa* project transforms yacht passageways into living environments using *Lunula*'s bioluminescent properties. Embedded within saline-filled architectural elements like handrails and panels, this living organism reacts to vibrations, touch, and sound, emitting an intermittent blue glow. To ensure the well-being of *Lunula*, the containment chambers have been designed to maintain a light-dark cycle of 12 hours, a sterile, CO_2-free environment, and nourishment derived from vitamins and trace metals. This dynamic lighting subtly traces movement, creating an immersive experience where the yacht appears responsive to human presence.

As an alternative lighting system, the *SeaBed* project applies *Vibrio fischeri*'s oxygen-sensitive bioluminescence to replace traditional fixtures (Figure 3). The project introduces adjustable lamps, a headboard illumination system, and a wave-inspired ceiling where bioluminescent liquid creates a soft, immersive glow. With the same concept at its core, another team presented *AquaCelestia,* reinterpreting bioluminescence as a tool for atmospheric enhancement in wellness spaces, particularly steam rooms and relaxation areas. By embedding *Vibrio fischeri* in gel mediums, the project envisions a yacht interior where light is cultivated rather than installed, introducing a new level of ambiance and interactivity.

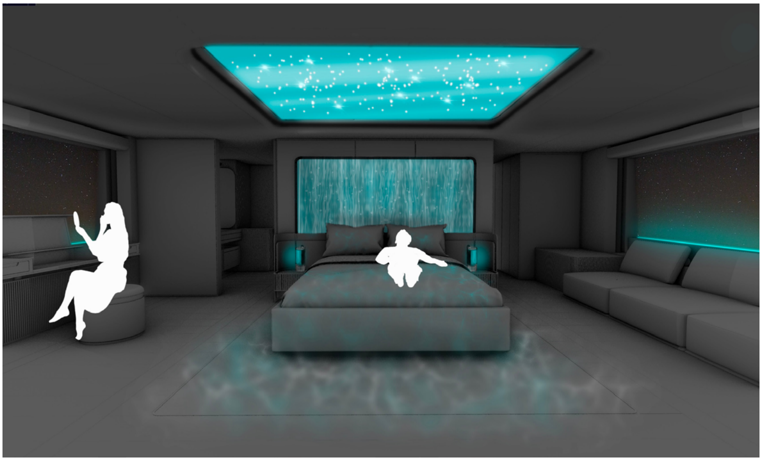
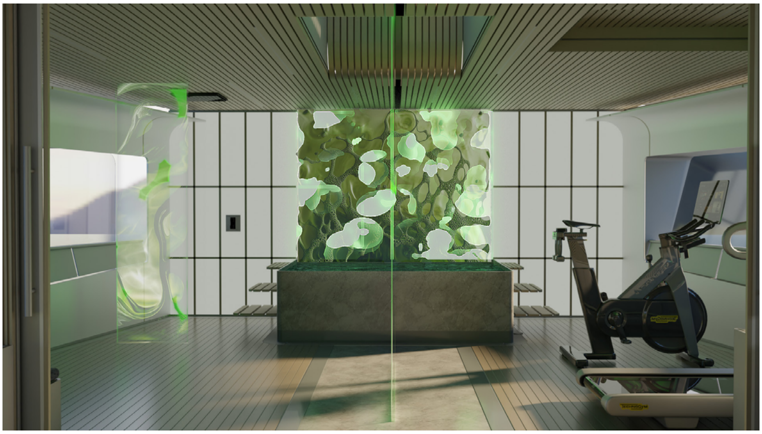


Figure 3.
SeaBed – Vibrio fischeri bioluminescence for a sustainable lighting system.

Rooted in the biophilic design trend, *EcoSense* reimagines the yacht's interior as a harmonious extension of nature, catering to wellness-conscious and sustainability-minded users. The project centres on lichens, which act as bioindicators, air purifiers, and resilient living elements. In spa and gym areas, lichen panels are sculpted into organic shapes responding to light and dynamically interacting with the environment. Additionally, stabilised mycelium panels enhance the yacht's bar and relaxation spaces with their organic textures, earthy tones, exceptional sound-absorbing properties, and structural flexibility.

Spirulini explores the integration of the cyanobacteria Spirulina and *Physarum polycephalum* to enhance yacht interiors with bioregenerative properties (Figure 4). Designed for wellness areas, the project features a spirulina partition in the spa that purifies air and separates areas, and a responsive spirulina wall in the gym that reacts to environmental changes. The yacht's bar incorporates a self-sustaining spirulina system, allowing guests to cultivate and consume it. Additionally, *Physarum polycephalum generates* soft ambient lighting and powers small-scale LEDs. By merging natural processes with interactive design, *Spirulini* transforms yacht interiors into living, evolving spaces that support both well-being and sustainability.

Figure 4. Spirulini – Blending Spirulina and Physarum polycephalum for bioregenerative wellness yacht interiors.



Beyond their visual impact, the developed projects are an exploration of designing with living organisms, where nature and technology converge to create a yacht interior that is dynamic, immersive, and deeply connected to the sensory experience of its passengers. Furthermore, the majority of projects play with textured surfaces, inviting tactile interaction. This aspect reinforces the concept of engaging passengers' senses through materiality and transforming passive relaxation spaces into immersive, evolving landscapes.

5.6 Workshop feedback

To better understand the impact of living materials in design, at the end of the activities, the participants were asked to answer an evaluation questionnaire on the workshop and the methodological process behind it. The majority of students have never heard of the integration of living materials and biological organisms in the design process. Thus, one of the key takeaways from the workshop was the increase in participants' knowledge about living artefacts.

As for the process, the *Understanding* phase received mostly positive feedback, with participants acknowledging that it was well-structured and integrated. The *Exploring* and *Applying* phases also received good ratings, with most participants finding them adequately supported by tools and activities. Many expressed that the methodologies introduced could be useful in their future projects and professional practice. Participants found the workshop's most valuable aspects to be the presentations and briefings by educators, the interaction with the teaching team, and the use of inspirational materials such as case study cards.

Despite the optimistic responses, certain challenges were highlighted (see Figure 5). Designing with living materials was perceived as particularly complex, and participants found the concept of sustainability to be both essential and difficult to implement in practical design scenarios. Suggestions for improvement included extending the duration of certain activities and providing more opportunities to observe living organisms and materials through tangible demonstrations.

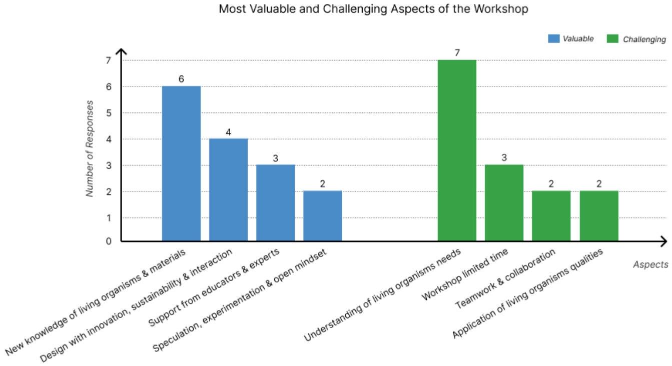


Figure 5.
Bar chart illustrating the most valuable and most challenging aspects identified by workshop participants in the questionnaire.

5.7 Reflections & discussions

This chapter delved into the speculative and interdisciplinary approach adopted in the *Living Materials for Yacht Design* workshop, emphasising how integrating living organisms into nautical interiors can enhance sustainability, immersive experiences, and unique functionalities. The workshop provided an initial platform to investigate the role of living materials in yacht design, offering theoretical insights and exploratory applications.

As the first attempt to introduce living materials into yacht design, the workshop provided valuable experimental ground for both educators and students to assess the feasibility and applicability of such practices. From a methodological point of view, the structured activities – inspired by established material design research frameworks – allowed participants to progressively engage with the notion of livingness, investigating their abilities to redefine onboard experiences. Through an iterative process of *Understanding*, *Exploring* and *Applying*, participants developed a critical awareness of living artefacts and their potential to transform spatial interactions. The increase in knowledge and the expressed willingness to explore this field in future projects underscore the topic's relevance within design education.

However, the workshop also highlighted key challenges in designing with livingness. One of the major limitations identified by participants was the lack of hands-on engagement with physical samples, which restricted their ability to fully comprehend material behaviours, growth patterns, and sensory properties of biological organisms. Unlike traditional material exploration, where texture, weight, flexibility, and resistance can be retrieved through technical specification, designing with living materials requires an understanding of biological processes, environmental dependencies, and long-term viability. Future iterations of this methodology should thus incorporate practical demonstrations, laboratory explorations, or biofabrication sessions that allow students to directly interact with living samples, fostering a more comprehensive material intelligence. Additionally, the nature of the workshop required participants to engage with design concepts that posed difficulties in translating living material proprieties into tangible design applications. Nevertheless, in this regard, case studies demonstrated their effectiveness as knowledge mediums and triggering tools.

Despite the speculative nature of the workshop, the proposed design scenarios were found to be feasible and contemporary, demonstrating a higher level of pragmatism and realism than initially expected. The projects confirmed the high potential of integrating biological organisms, particularly in fostering adaptive, responsive, and regenerative design solutions. The concepts, engaging with bioluminescence, air purification, and bio-integrated wellness spaces, proved how living materials can enrich yacht interiors, creating a customised sensorial experience.

While the field remains largely experimental, the findings from this experience indicate how the introduction of livingness represents a real opportunity to rethink traditional interior yacht design paradigms, fostering a new relationship between humans and materials and enhancing the surrounding natural environment.

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6. Co-habiting with living artefacts: designing a living biofilter for dishwasher wastewater upcycling

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ABSTRACT

The co-habiting experience presented in this chapter focuses on bacteria as components of living artefacts. It is founded on current results of the Jetsons' kitchen project developed by an interdisciplinary group of researchers from the Department of Design of Politecnico di Milano and the Department of Biology of Università di Roma Tor Vergata. The project is aimed at upcycling dishwasher wastewater in plant irrigation taking advantage of an *ad hoc* engineered biofilter based on a microbial consortium. This experience was conducted through a workshop planned for interaction and product design students of Politecnico di Milano, who were asked to design contextual applications of the wastewater biofiltering system. The participants designed the shape of the biofilter based on the *ad hoc* microbial consortium, speculating on forms and interactions according to the given product requirements and expanding from envisaged user-based scenarios (home, co-working, Horeca) provided by the research group.

6.1 Introduction

The Jetsons' kitchen research project aims to integrate the reuse of grey water from household appliances in the cultivation of edible and ornamental plants (Costa *et al.*, 2018; Costa *et al.*, 2019; Alabiso *et al.*, 2023). The interdisciplinarity of the project required collaboration in a research group involving designers and architects from the Department of Design of Politecnico di Milano and microbiologists and biotechnologists from the Department of Biology of the Tor Vergata Rome University.

A primary finding of the Jetsons' kitchen project is the Zero Mile system (Figure 1), an experimental prototype specifically developed for the treatment of the dishwasher wastewater and the cultivation of a vegetable garden.

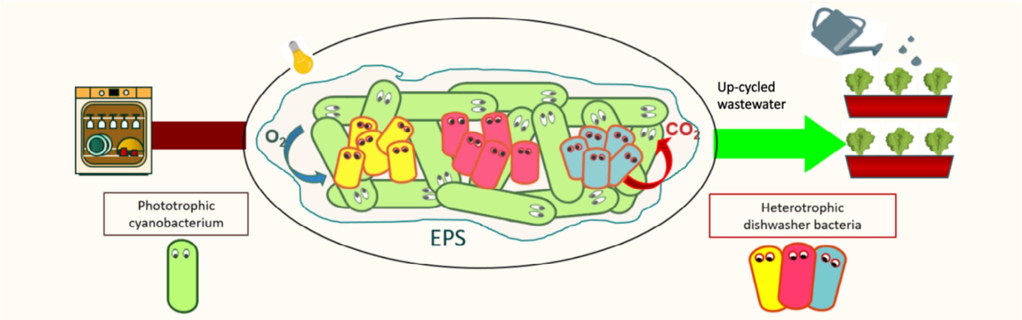
Figure 1.
Zero Mile experimental prototype with external biofilter.

The Zero Mile biofilter, currently contained in a polypropylene box, is based on an *ad hoc* microbial consortium made up different microorganisms selected to work together and to perform a biodegradative process, transforming wastewater into a resource for both vegetable irrigation/fertilization and subsequent dishwasher rinsing cycles. The *ad hoc* engineered consortium consists of different microbial partners: an autotrophic nitrogen-fixing cyanobacterium called *Trichormus variabilis* from the collection of the Tor Vergata Algae Biology Laboratory and three aerobic heterotrophic bacterial strains (*Acinetobacter* sp., *Aeromonas* sp. and *Exiguobacterium* sp.) isolated from dishwasher wastewater (Congestri *et al*., 2020).

The consortium displayed important emergent properties: a three-dimensional (3D) organization, as a blue-green suspended aggregates (biofilms), not adhering to the container surfaces, whatever the material is (plastic or glass). The aggregate takes the shape of the growth vessels. The 3D structure is reversible, and can be disaggregated by strong shaking, but it quickly reconstitutes if the container is left to rest.

The cooperative interactions between autotrophic and heterotrophic bacteria is based on the complementary metabolic activities of the partners: the heterotrophic bacteria attack and degrade food leftovers producing carbon dioxide and consuming oxygen, while cyanobacteria consume carbon dioxide and produce oxygen through photosynthesis (Figure 2). The exchange of carbon dioxide and oxygen among partners allows to remove food leftover from wastewater, mineralizing their nutrients which, in their inorganic form, can be utilized by all the microbial partners to produce microbial biomass or can be used as plant fertilizer by watering with treated wastewater.

Figure 2. Symbiotic relationship between heterotrophic and autotrophic microbial partners in the biofilter.



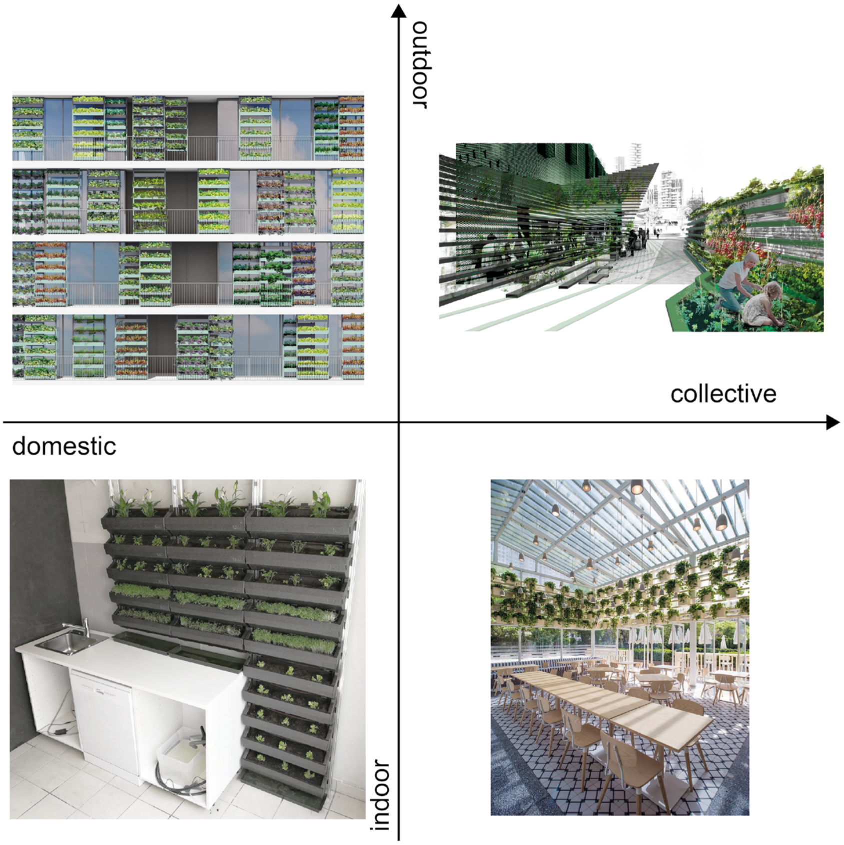
Overall, the bacterial metabolic processes allow to ameliorate the wastewater quality by significantly reducing the nutrient concentrations (as total nitrogen and phosphorus).

The analysis and experiments carried out by the biologists to understand the physiological characteristics of the microbial consortium and to optimize its survival and thriving conditions, were determinant to define the biofilter design and topology requirements (Alabiso *et al*., 2023).

Another intermediate finding of the Jetsons' kitchen project is the expansion of the application scenarios from indoor to outdoor spaces and from the domestic kitchen to collective spaces (Figure 3) such as co-working, hotels, restaurants and canteens (Buratti, Nebuloni & Meraviglia, 2019; Volonté & Grana 2020). Consequently, the need raised to shape the biofilter speculating on different forms and interactions depending on the intended scenario and the related users.

However, one of the limitations of the research so far is the lack of

Figure 3. Jetsons' kitchen application scenarios.



a suitable design for the biofilter as a product. Therefore, the workshop becomes an opportunity to bring out, from an idea generation process useful suggestions to reach a prototyping and field validation stage, also useful to increase the Technology Readiness Level (TRL) of the experimentation.

6.2 Methodology and workshop structure

The Workshop builds on an interdisciplinary approach combining experimental methodologies, mainly characterization of wastewater, plant growth and functionality analysis, with User Centered Design techniques (Norman & Draper, 1986) and a Research through Design approach (Stappers, Sleeswijk & Keller, 2014), involving users in different steps of the research, taking advantage of demonstrators and prototypes in subsequent phases of refinement and working in a multidisciplinary team of teachers, researchers and students. The workshop activities fit into this strand specifically exploring the development of the wastewater biofiltering system in its contextual applications. The heterogeneity of the fields involved has resulted in the need to define a shared glossary to integrate such complexity of scientific approaches and disciplinary languages.

Research and analysis of literature and case studies preceded the workshop, which was prepared through meetings involving the Jetsons' kitchen research group, the coordinating members of the Relive project and the workshop's responsible professor and tutor.

The workshop's structure was organized in the phases of *Understanding*, *Exploring*, and *Applying* (Figure 4), comprehending lectures on the Relive and Jetsons' kitchen projects, on microorganism biology and biofiltering technologies and on design tools such as User Journey and Task Analysis; guided and autonomous group work; reviews with the interdisciplinary teaching staff and collective presentations on context, concept and final proposal.

A questionnaire was administered to the students at the end of the activities to assess their experience and gain insights regarding the workshop and the underlying design process.

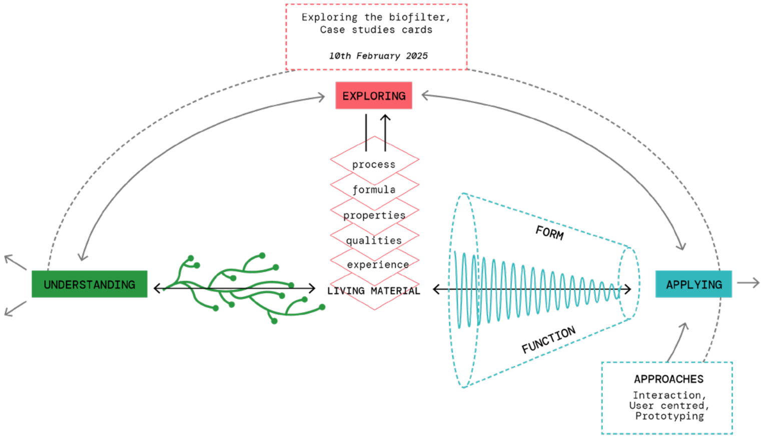


Figure 4.
The framework of Understanding, Exploring and Applying stages.

Understanding

Information on the overall research projects and on the envisaged user-based scenarios (home, co-working, Horeca) were anticipated to the students one week in advance to give them time to reflect and do preliminary research on the scenario they choose and on biofiltering applications.

Exploring

The workshop took place at Politecnico di Milano Design School from 10 to14 February 2025 involving 38 design students organized in 8 groups with mixed background on product, interaction design, communication, interior design and architecture.

Ideas generation has been stimulated through the case study cards presented in the chapter *Exploring livingness through case study: an annotated portfolio* by Valeria Regis and through some stimulating questions (Figure 5).

Applying

The participants were asked to design the shape of the biofilter containing the *ad hoc* microbial consortium according to given product requirements, reflecting on the biofilter aesthetics and symbolic qualities and speculating on forms and interactions between living matter and container and between the biofilter and the user. Finally, they were required to present their proposal highlighting the contextual application, displaying drawings and models of the biofilter and describing the user journey.

Figure 5.
Questions for idea generation proposed in the workshop.

During idea generation ask yourself

Where can the consortium be kept?
- Should it be visible or hidden?
- How is the biofilter structured?

How does the user know if the consortium is healthy?
- Is this communicated? If so, how? Physically or digitally?

What happens when the consortium grows?
- How does the user know when/how to clean the container and restart the biofilter?
- How does the user know when the consortium has grown too much and needs to be partially removed?
- Is a specific tool needed to remove the consortium when it grows too much? Or is it an automatic process?
- Knowing that the consortium can act as a fertilizer, what can the user do with the excess?
- How is the information communicated to the user? Through an embodied interface, an app, or another method?
- Knowing that the consortium can act as a fertilizer, what can the user do with the excess?
- How is the information communicated to the user? Through an embodied interface, an app, or another method?

Could the design of the biofilter evoke other meanings and trigger further reflections beyond its functional purpose? If so, how can this be communicated?
- How are concepts typical of "livingness" such as temporality, unpredictability, and care of the biofilter communicated to the user?

6.3 Workshop activities and results

The first result consists in the identification of eight use scenarios (see project cards) – three apartments, two workers shared spaces, three restaurants – classified according to following categories:

- context of use: domestic/coworking/horeca;
- user profiles: individual, couple, family/staff/guest;
- user roles: take care of biofilter, take care of cultivation, eat the vegetables, enjoy the plants;
- mode of use: private/collective
- positioning of the biofilter: indoor/outdoor;
- positioning of the plants: indoor/outdoor.

Figure 6.
Biofilter requirements summary presented in the workshop.

Biofilter Requirements

Light
Ensure uniform illumination
e.g.
- *Design a transparent container*
- *Design the shape to maximise the illuminated surface*
- *Design an artificial lighting system for indoor and unlit settings*

Temperature
Keep temperature between 15 and 30°C
e.g.
- *Design an insulation/ heating/ cooling/shading system*
- *Choose selective materials*

Air
Ensure the container sealability during the process
e.g.
- *Consider an openable structure*
- *Integrate an airtight lid*

Configuration & Precautions
Provide best working conditions for consortium
- *Design a container (or more containers) with 15 l overall capacity and input/output holes of 15 mm*
- *Position the input hole at a level higher than the contained wastewater*
- *Position the output hole at a level higher than the level of the consortium to prevent its damage*
- *Design a container without sharp edges*
- *Integrate with solutions for monitoring wastewater temperature and composition*

Feeding & Maintenance
Facilitate consortium inoculation and cleaning
- *Provide washable and sterilisable container (resistant to alcohol or UV and basic pH wastewater) with materials like polystyrene or glass*
- *Ensure cleaning and restarting the system every around 6 months by notifying the user*
- *Design tools for feeding and restarting*
- *Design tools to extract biomass excess each 3 months*
- *Provide consortium health monitoring*

In the three apartment scenarios the use is obviously private. The users are a couple, a family and a group of students' flat mates, who take all care of the biofilter and cultivation in an increasing organized way and enjoy the plants. In the first case (Life) both the biofilter and the vegetable cultivation are in the indoor space, in the second case (Ecoflow) the biofilter and the cultivation of ornamental plants are in an interior patio and in the last case (Mizu) both biofilter and vegetable cultivation are outdoor, in the kitchen terrace.

The two workers shared spaces, a shared kitchen of a university department (Poligreen) and a breakout room of a design studio (Halo), are used collectively. In the first case the users are only the workers using the kitchen and performing all roles regarding biofilter and ornamental plants cultivation, in the other the staff takes care of biofilter and vegetable cultivation, while also guests can interact with the biofilter and enjoy the plants. In both cases biofilter and cultivation are in the indoor space.

The three Horeca scenarios regards a restaurant (Fernie) and two hybrid spaces (Lumea and Biowave) combining restaurant and café. In the hybrid spaces the use is collective, the staff is in charge of biofilter management and cultivation of ornamental plants, with specific roles assigned to different professional figures; guests can enjoy the plants. In all cases the biofilter and the cultivation are in the indoor space. In the restaurant scenario it's the staff managing biofilter and cultivation, and guests eating and enjoying the plants.

Preliminary studies aimed at defining the biofilter, highlighted the importance of factors, such as shape, color, and illumination of the container (Alabiso *et al.*, 2024). Consequently, direct experimental trials were conducted during the workshop to assess the biofilter lighting and the behavior of the microbial consortium under different physical conditions.

The first test involved illuminating the sample tubes using an RGB LED strip. This setup enabled the assessment of the impact of a colored lighting system on the container, wastewater, and biomass. Light plays a fundamental role as an energy source in initiating the photosynthetic process. Therefore, prior to the experimental phase, key parameters influencing photosynthesis were considered:

- photosynthesis consists of two main phases, the light-dependent and light-independent (dark) reactions, which determine the alternation between the day-night cycle and potential illumination schedules;
- the efficiency of photosynthesis is influenced by light quality (wavelength) and intensity, which affect the rate of the process;
- chlorophyll predominantly absorbs blue (450 nm) and red (680 nm) light while reflecting green wavelengths. This consideration allowed the exclusion of non-contributory frequencies and wavelengths from the experimental setup.

Following these parameters, a small-scale experimental setup was designed. The LED strip was positioned in different configurations around the sample tubes, varying the distance, angle, and direct contact with the container. The different lighting arrangements were tested to evaluate their impact on system performance and adherence to experimental requirements. Additionally, a preliminary assessment of the visual impact of light placement was conducted to explore its implications for the design of the biofilter (Figure 7).

As already reported, a key characteristic of the microbial consortium is that it does not stick to the container and conforms to its shape. Additionally, when disaggregated, it spontaneously reassembles. Disaggregation occurs upon vigorous shaking, while reassembly

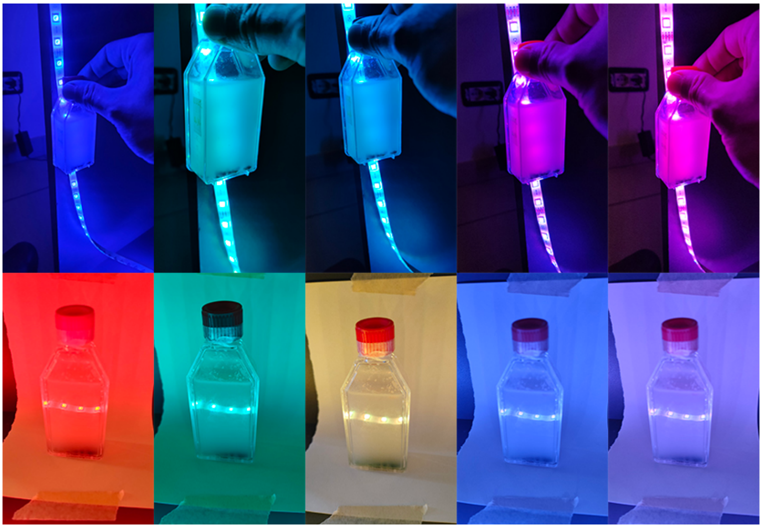


Figure 7. Experimental test with light.

takes place within approximately 9 hours. Complete aggregation restoration is observed within 12 to 24 hours (Alabiso *et al*., 2023).

Based on these properties, a second test was conducted to evaluate the aggregation behavior of the consortium and to document its response in containers of varying shapes and sizes.

To achieve this, objects were selected to simulate alternative configurations for the biofilter container. Experiments were performed using Plexiglas tubes of different diameters (Figure 8a), as well as commonly used plastic and glass cups and containers (Figure 8b). An additional trial involved the use of fabric pieces and plastic nets to assess the consortium's ability to aggregate in both irregularly shaped supports and on structured surfaces (Figure 8c).

The results confirmed previous findings obtained using standard laboratory containers (e.g., flasks, cell culture bottles). Specifically, regardless of the shape and size of the container, the consortium consistently exhibited aggregative behavior, settling at the bottom and conforming to the container's shape.

Specific design requirements for the biofilter included the following:

- ensuring system cleaning and restarting approximately every six months, with user notification;
- designing tools for feeding and system restart;
- developing instruments for the removal of excess biomass every three months.

Figure 8.
Tests on container shapes: tubes (8a), cups (8b), irregular surfaces (8c).

To address these requirements, a final experimental test was conducted to evaluate different methods and tools for biomass removal. The procedure involved aspirating a portion of the biomass using laboratory pipettes and syringes. Additionally, various mesh structures, shaped differently, were tested to capture and extract biomass directly from the containers (Figure 9). The final outcomes are the eight biofilter (Figure 10) contextual application proposals reported in the Annex II. They span from a dispencer (Halo) and a self-standing device (Lumea), through biofilters aggregateted to the dishwasher (Poligreen), integrated in the kitchen furniture (Life) or in a bar counter (Biowave) and biofilters contiguos (Mizu) or hosted (Ecoflow) in vertical gardens, to a modular wall system integrating biofilter, treated water reservoir and cultivation (Fernie).

6.4 Conclusion and future development

Participants of the workshop had varied educational and cultural backgrounds, different professional and academic experience that made the interaction initially complex, but at the same time gave the opportunity to share approaches and expertise between teachers and students.

The students' answers to the questionnaire on the content and the methodological process revealed that most of them did not have previous knowledge about living artefacts and were able to increase

Figure 9.
Test to remove biomass in excess.

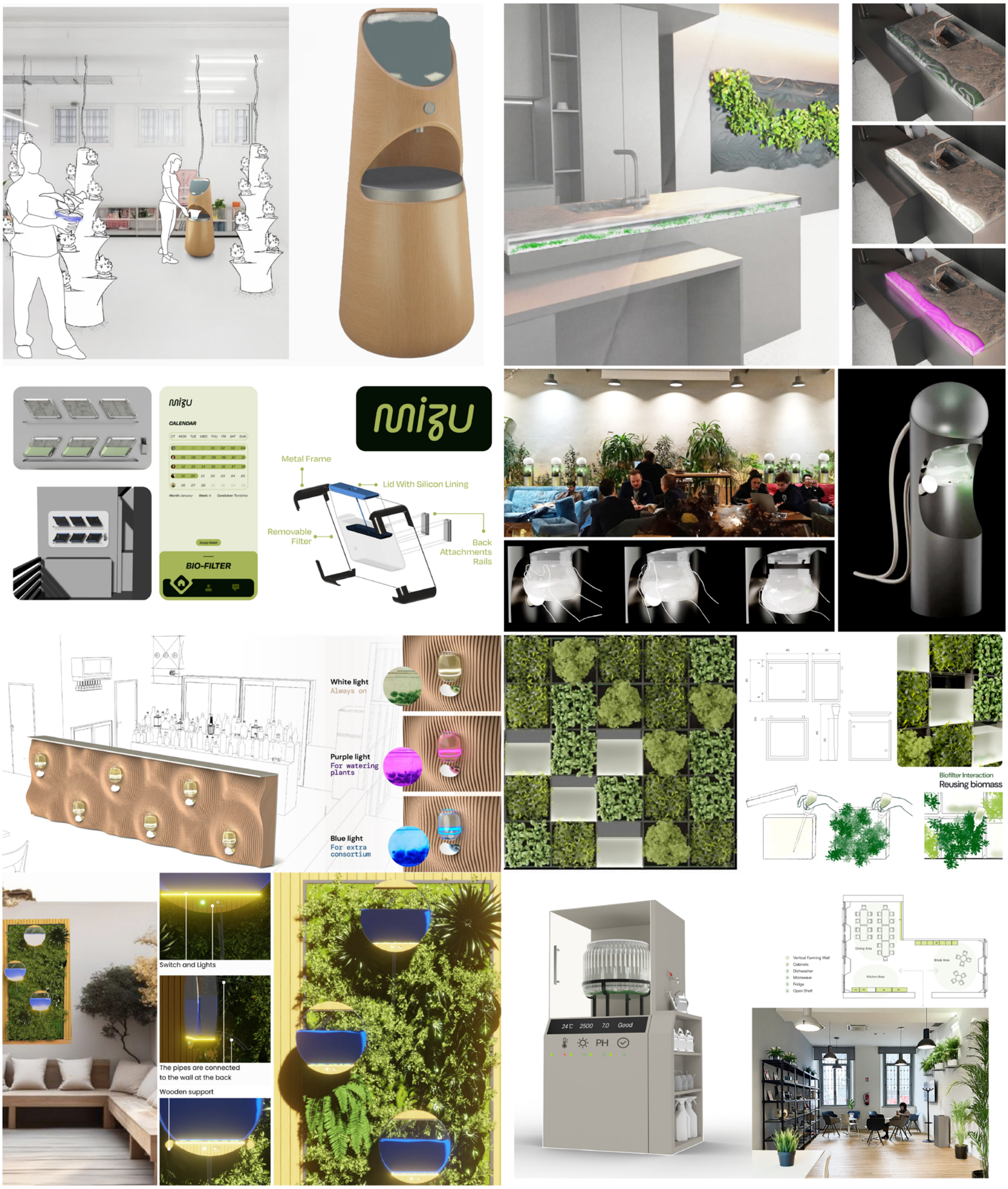


Figure 10.
The final outcomes are the eight biofilter. From left to right, up to down: Halo, Life, Mizu, Lumea, Biowave, Fernie, Ecoflow, Poligreen. Images Credits from the authors of the projects.

it through the workshop. As for the process, the *Understanding* phase received mostly positive feedback, with participants stating that it was well supported and impactful to the design project. The *Exploring* and *Applying* phases received almost as good ratings, with the relevance as the most acknowledged dimension. Many students expressed that the methodologies introduced could be useful in their future projects and professional practice and were satisfied with the workshop. Most valuable aspects were found in working with living artefacts and seeing the microbial consortium and the most difficult to understand all the requirements and the detailed processes.

The ideas generated and sharing of experiences during the workshop allow some considerations to be made regarding functional and emotional interactions. The shape of the biofilter container and in particular its base turned out to be very relevant, it can be corrugated to distribute the biomass and ease the extraction of the exceeding part, and it offers an interesting viewpoint to the consortium to enhance the aesthetics quality of the artefact. Colored and pulsing light can be used to communicate the maintenance status of the consortium, to mitigate the murky appearance of the treated wastewater and to communicate livingness at an emotional level. Blue and red wavelengths, highly effective for photosynthesis, reviles to generate also very pleasurable effects. Data collected by the sensor system, beyond being used to manage the correct functioning, can be communicated to users to reinforce engagement and awareness.

A notable advancement to solve the specific problem of the removal of excess biomass is the «shake for replacement» idea conceived by Poligreen project team. The idea takes advantage of the characteristics of the consortium to disaggregate when shaked, proposing to remove the excess in the suspended state. Other remarkable reflections regard the reorganization of the hydraulic module aimed at displacing the treated wastewater contiguously to the biofilter or to the cultivation.

Regarding the contextual integration of the biofilter, interesting alternatives emerged such as the self-standing dispenser typology, the integration in the kitchen sink block and the modularity of biofilter, tanks and cultivation elements.

Future developments in the short term will consist in the realization of mockups of sample biofilter proposals to be displayed in the final exhibition of the Relieve project. The development of a working prototype to be integrated in the Zero Mile system is foreseen in the middle term. In a wider perspective, knowledge and solutions emerged for the dishwasher wastewater biofilter can be transferred to the washing machine biofilter already under study by the Jetsons' kitchen research group and finally be integrate in the development of grey water biofilters.

Furthermore, the outcomes of the workshop will serve as a foundational input for a computational design process, originating from the Jetsons' kitchen project, to investigate a cultivation system structured around discrete elements.

Acknowledgement

The authors would like to thank all the participants (Figure 11), specifically Nicola Besana, Giorgia Burzio, Venere Ferraro, Nicla Guarino, Margherita Pillan and Valeria Regis for contributing to the workshop organization and activities, and all the students who participated for the creativity and commitment they bared in developing their proposals.

Figure 11.
Workshop participants.

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7. Soft living artefacts: design-driven exploration of engineered living materials

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ABSTRACT

In recent years, design scholars have introduced Living Artefacts as a novel class of objects that are alive, responsive, and relational. A promising yet underexplored area lies at the intersection of design, Human Computer Interaction and synthetic biology. In this context, Engineered Living Materials (ELMs), developed by bioengineers, show life-like traits such as self-regeneration, autonomy and environmental responsiveness. These materials could inspire the design of soft robots and artefacts that support well-being. This chapter presents findings from a Studio conducted at the TEI25 Conference in Bordeaux, where participants explored an ELM, an augmented silicone embedded with proteins, through hands-on, design-led experimentation. The session examined the potential of ELMs beyond bioengineering and prompted critical reflection on opportunities, challenges and ethical considerations at the convergence of bodies, design and living matter.

7.1 Introduction

Design research has increasingly explored the integration of living organisms such as algae, bacteria, fungi, and plants into the design process and design outcomes. This tendency translates into material choices aimed at reducing the environmental footprint of products while also expanding material expression. The use of bio-based materials, which are derived from living or once-living substances, shows important opportunities due to their biodegradability and for their sustainable life cycles. This shift in material innovation reflects a growing commitment in reducing environmental impact in interactive product design (Blevis, 2007), while also fostering new sensory experiences that engage users with physical matter in novel ways (Bell *et al.*, 2022; Lazaro Vasquez *et al.*, 2022).

Despite these advancements, many bio-based design outcomes merely mimic the aesthetics of living organisms rather than embodying true biological functions. In response, a new wave of Biodesign research is emerging to extend the concept of Livingness, shifting from objects that merely contain biological elements toward products that sense, grow, adapt, and eventually decay as part of their lifecycle (Karana *et al.*, 2020). This perspective challenges traditional ideas of material permanence, inviting designers to embrace temporality and transformation as inherent process of any designed artefact.

Parallel to these developments, the field of Human-Computer Interaction (HCI) has increasingly focused on materiality as a lens for design, investigating how materials shape and mediate interactions. Rasmussen *et al.* (2012) propose a framework for shape-changing interfaces, where shape change is increasingly used in physical user interfaces, both as input and output. Moreover, researchers have explored material programming as a way to develop novel interaction modalities, including temporality in interaction design (Vallgårda *et al.*, 2013), somaesthetic explorations (Tsaknaki, 2021), and tension-and-release mechanics (Winters *et al.*, 2022). These approaches draw inspiration from biological and natural systems, mimicking their dynamic, responsive, and adaptive behaviors to create richer, more embodied interactions between humans and machines. Several researchers are experimenting with Interactive, Connected, and Smart

(ICS) materials, giving purpose and applications to advanced materials through a design-oriented approach (Parisi *et al*., 2024).

Another promising direction focuses on soft systems – flexible, organic, and often biologically inspired materials that mediate human-technology interactions. For instance, Soma Design (Höök *et al*., 2019) and Vibrant Wearables (Tsaknaki *et al*., 2021) investigate how technology can be embedded into materials that not only conform to the body in an unintrusive way, but also respond to its movements, rhythms, and affective states. These explorations push beyond conventional rigid interfaces, suggesting a future in which interaction is fluid, organic, and intimately connected to the user's physical and emotional experiences.

7.2 Engineered living materials and soft robots

Advanced materials with life-like qualities, such as sensing and adaptability, are becoming key to designing next-generation interactive systems. Parallel to this, synthetic biology is opening new interdisciplinary opportunities, particularly with the development of Engineered Living Materials (ELMs) – materials designed by bioengineers to exhibit self-regeneration, environmental responsiveness, and adaptability. Nguyen *et al.* (2018) define ELMs as engineered materials composed of living cells that form or assemble the material itself, or modulate the functional performance of the material in some manner. These features surely hold exciting potential for interaction design where the interaction is deeply tied to materiality.

Within this context, soft robotics stands out as a particularly promising field. Soft robots, constructed from highly flexible materials that imitate living tissues, can perform tasks that rigid robots struggle with, such as delicate manipulations and organic, fluent movements. Despite their widespread use in biomedical applications, their role within HCI and interaction design remains underexplored. Yet, their ability to respond, adapt, and interact physically suggests new design possibilities, particularly in Tangible Interaction Design, where material and form influence user engagement.

Escaida *et al.* (2025) present an interactive art piece that combines soft robotics with tactile engagement, exploring the sensual and responsive potential of robotic systems. The installation features soft, flower-like robotic structures that respond to human touch, inviting participants to experience a unique form of human-robot interaction that emphasizes intimacy and sensory connection. A sustainable solution to soft robots is presented by Den Teuling *et al.* (2024) presenting chitosan, a widely available biodegradable actuator that absorbs moisture from air and undergoes shape changes in response to fluctuations in humidity (Figure 1). Besides the material, the researchers conducted generative sessions where participants interacted with the chitosan films, giving suggestions to the user interaction and experience of such material.

Figure 1.
Chitosan sustainable actuator (Den Teuling *et al.*, 2024). Photo Credits from the authors of the projects.

Grasping the user interaction with this new class of material is deeply relevant. On this regard Brocker *et al.* (2023) provide a comprehensive map of soft robotics shapes investigating how such shapes influence user perceptions and associations. The study provides insights for developing soft robotic devices that align with user expectations and enhance overall experience. Ultimately, as advancements in ELMs and soft robots continue to unfold, new opportunities emerge for interaction design that moves beyond rigid, static interfaces toward more fluid, adaptive, and sensory-rich experiences.

7.3 Studio's overview and structure

To delve deeper into these possibilities, the author (together with Professor Venere Ferraro, Professor Neel S. Joshi, and Valeria Regis) conducted a design Studio at TEI 25 (Tangible, Embedded and Embodied Interaction) conference in Bordeaux, France.

The Studio explored three artefacts designed for sensory and intimate interaction with the body: a menstrual cup, a breast pump, and a sex toy. These products come into direct contact with the body—around it and, in some cases, even within it. Particularly the sex toy chosen was dual-use toy, versatile sex toy working for both grinding (external stimulation) and stroking (penetrative or stroking motion).

Currently, all three artefacts present several user experience and usability challenges that could potentially be improved through the enhanced properties of the augmented silicone. These challenges range from design and material choices to interaction, adaptability, and accessibility for diverse user groups. The Studio had three goals:

1. exploring how ELMs could enhance traditional materials, giving them new functional properties;
2. examining how soft robots could improve user experience in the analyzed artefacts;
3. critically reflecting on interdisciplinary collaboration between design and biology in creating Living Artefacts.

Through iterative prototyping and discussions, participants explored how ELMs could transform the usability, comfort, and interaction of these artefacts while addressing the challenges and ethical considerations of integrating living materials into everyday products.

The Studio's structure followed an adapted framework (Figure 2)developed during the former Erasmus+ project DATEMATS (Ferraro V. 2021).

- *Understanding*: this phase concerns getting the fundamental body of knowledge as first step of the process. In the Studio this phase were two presentations, one about the project and another one about the augmented silicone held by Professor Joshi. Participants were introduced to ELMs learning what they are, how they are programmed, and explore their *augmented* life-like abilities.

- *Exploring*: the emphasis on the designer getting knowledge on the materials and processes by documenting and evaluating. Participants divided into three groups began by mapping both the areas of improvement of one of the chosen artefacts, in terms of user experience, and the *superpowers* of the silicone (for instance, a programmed material behavior in response to an input).
- *Applying*: From an ideation phase supported by canvases provided by the organizers, participants drafted scenarios, thinking about specific user and context of use. The challenge was to understand how a specific behaviour (programmed within the material) could improve usability of the artefacts. From this process, participants developed their idea, further representing their scenarios of interaction visually and through physical mock-ups.

The Studio was an immersive, full-day experience, culminating in a closing roundtable where participants shared their outcomes and reflected on the process they followed. A key highlight was the diverse disciplinary backgrounds of the participants – some adopting a material-driven design approach, while others focused on a human-centered perspective. This diversity in approaches to livingness fostered dynamic discussions, demonstrating that an interdisciplinary lens is valuable when designing living artefacts.

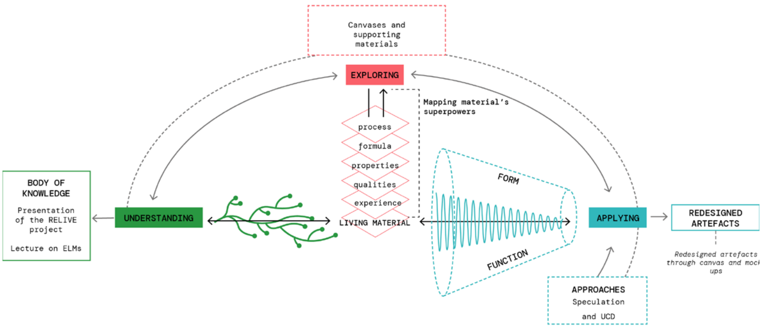

Figure 2.
The DATEMATS process adapted to the Studio.

7.4 Materials explored

The key focus was augmented silicone, a material developed by Professor Neel S. Joshi's research team at Northeastern University, which embeds proteins within silicone to enhance its electro-mechanical properties. Silicone is already used for soft electric actuators, but with embedded proteins, it could lead to lighter, more energy-efficient, and more responsive interactive materials. Examples of potential future applications include wearable actuators capable of augmenting and supporting human movement, such as an assistive sleeve for lifting heavy objects.

Figure 3.
The three artefacts.
Photo Credits from the authors of the projects.

We explored two kinds of materials. On the one hand we looked at three products carrying several issues related to user experience: menstrual cup, breast pump and sex toy (Figure 3). On the other hand, bioplastic films and augmented silicone with embedded proteins, programmed to carry out specific tasks. The silicone rubbers with embedded proteins can be compared to the same rubber composition without the embedded proteins to directly experience the difference in their *feel* (i.e., mechanical properties) in a tactile manner. For this reason, regular silicone was brought for building low fidelity prototypes, among other materials. Since the augmented silicone is still in a development phase, the outcomes of this Studio are speculative artefacts and scenarios.

To guide the ideation process, the organizers provided participants with a structured canvas and a set of supporting cards (Figure 4). The canvas was carefully designed to align with the three phases of the DATEMATS process (Understanding, Exploring, and Applying) to systematically lead participants from the identification of user experience issues, to the ideation of potential solutions. In the Understanding section, participants were encouraged to analyze the current user experience of specific artefacts, focusing on identifying pain points, limitations, and challenges that regular users encounter. This step ensured that ideas for improvement were grounded in real user experiences. In the Exploring section, participants picked one of the *superpowers* associated with the augmented silicone. These *superpowers* represented unique properties or functionalities that could potentially enhance user experience and usability. Participants were guided to explore and experiment with these superpowers, matching them to the challenges they had previously identified. Finally, in the Applying phase, participants selected and integrated the most promising superpower(s) into their design concepts, envisioning how these material properties could lead to tangible improvements.

To further support participants, especially those who had not personally used the artefacts under discussion, the organizers also provided a set of hint cards. These cards included pre-identified pain points related to different artefacts, offering concrete examples to spark discussion and ideation. For instance, in the case of menstrual cups, the cards listed common challenges such as:

- difficulty in removing the cup without discomfort or pain;
- the cup not easily coming out, requiring effort or specific techniques;
- a sensation of the cup feeling like a foreign object inside the body;
- discomfort related to dealing with menstrual blood;
- hygiene challenges, especially in public restrooms without access to water or private spaces.

These hint cards served as a valuable tool, ensuring that all participants – regardless of prior experience using the artefacts – had a clear starting point for ideating potential solutions leveraging the life-like properties of the silicone.

7.5 Studio results

The results of the workshop reflected the diverse backgrounds and perspectives of the participants. Some approached the challenge with a more user-centered mindset, while others focused on the material itself. Despite these differences, all the resulting ideas leveraged the unique properties of augmented silicone to address issues in the user experience (Figure 4). Four ideas are presented here in detail, followed by final considerations in the concluding section.

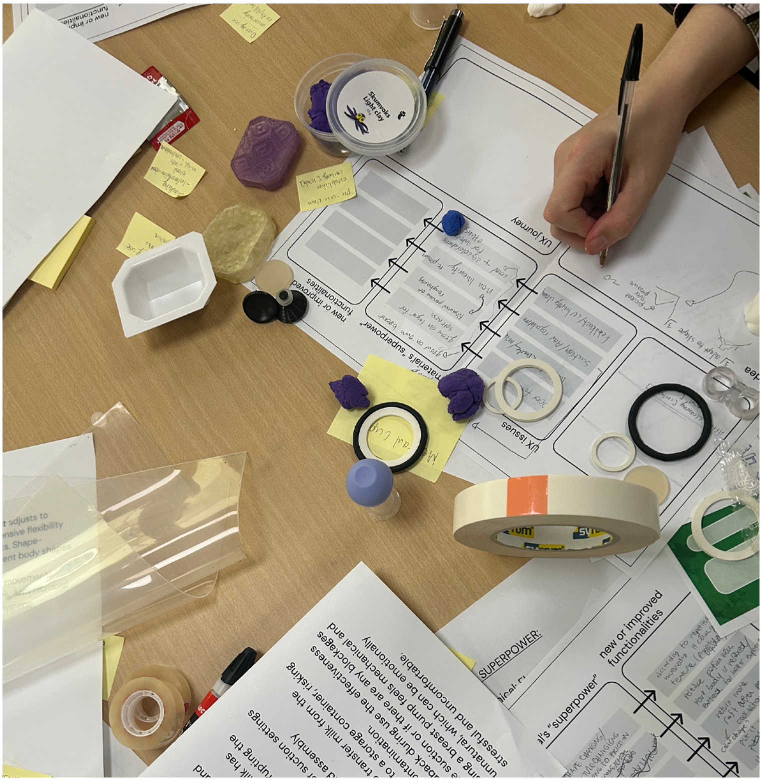

Figure 4.
Filling the canvas while developing mock-ups in silicone.

7.5.1 Augmented sex toy

This idea began with the user journey of a sex toy, divided into three phases: pre-use, during use, and post-use. In the pre-use phase, there is high anticipation and excitement. During use, the experience is often characterized by frustration, with common thoughts including: «sticky», «cold», «too plastic», and «unsure if I'm using it correctly». The post-use phase is marked by disgust, with the primary concern being, «how do I properly clean it?».

With new and improved functionalities, the user journey becomes an interactive experience, where the object adjusts to the body's responses, providing a more engaged and personalized encounter (Table 1).

UX issue	Material *superpower*	New or improved functionalities
Low stimulation	Shape-changing texture according to friction	According to repetitive movements it changes texture
Feels too *plasticky*	Contraction sensors	Returning softer when sensing contraction
Unsure about the correct usage	Hormone sensors	Releasing scent when the body is relaxed for a better experience

Table 1. Augmented sex toy, summary table.

7.5.2 Personalized breast pump

This idea stemmed from the widely perceived discomfort of breast pumps, which are often seen as painful and not adaptable to different body shapes. The user journey describes an uncomfortable, impersonal interaction with the machine, leading to negative experiences for the user (Table 2).

UX issue	Material *superpower*	New or improved functionalities
Poor fit	Growing into a surface and taking the shape/texture	Growing a bacterial cellulose layer adapted to each one's nipple conformation
Suction and flow regulation	Contraction sensors	Getting firmer and returning softer according to the suction

Table 2. Personalized breast pump, summary table.

The improved user journey with these new functionalities focuses on a more intimate, less painful, and personalized breastfeeding experience. This solution could offer a more inclusive and adaptive approach to accommodate various body shapes and comfort levels, eliminating the need for users to adapt to the machine.

7.5.3 Responsive menstrual cup

The menstrual cup was the chosen object for this idea. The user journey is divided into three phases: pre-use, during use, and post-use. In the pre-use phase, users feel a sense of pride for choosing a more sustainable option. However, during use, the main feelings shift to discomfort due to the challenges of insertion and hygiene, particularly in public spaces. Users often experience uncertainty and fear of losing control, as it can be difficult to determine when the cup is full, especially with a heavy flow. Post-use frustration arises due to the difficulty in removing the cup and the messiness involved, especially because the cup can become very dirty from the blood.

With the new and improved functionalities, the user journey becomes more secure, helping in both inserting and removing the menstrual cup, while ensuring a cleaner and more controlled experience (Table 3).

Table 3. Responsive menstrual cup, summary table.

UX issue	Material *superpower*	New or improved functionalities
Missing information about blood level	Shape-changing texture	Changing texture in the stem to notify blood level
Difficult to fold to insert it	Mechanical properties (slowly returning to the original shape)	*Blocking* the cup for 20 seconds while inserting it then slowly releasing it
Difficult to remove it	Shape changing textures and mechanical properties (slowly returning to the original shape)	Clicking the stem and the cup *shrinks*, changing texture to facilitate removal

7.5.4 Final considerations

The three ideas presented are some of the ones developed during the Studio. They suggest the potential of Engineered Living Materials to support better user experiences. Each concept uses augmented silicone's unique properties – such as shape-changing textures, mechanical responsiveness, and sensor integration – to address common issues faced by users while approaching menstrual cups, sex toys, and breast pump. Whether it's improving comfort, personalization, or the overall user experience, these ideas while speculative suggest compelling possibilities for enhancing livingness within product and interaction design through material innovations.

At the end of the Studio, participants and organizers engaged in an open discussion to gather feedback on how the activities were conducted throughout the day, as well as on the tools introduced. The Understanding phase was considered well-integrated into the agenda and highly relevant to the design process. The Exploring phase was also deemed relevant, but participants noted that they could have benefited from more structured sub-tasks rather than the open-ended approach used in this case. The Applying phase was found to be effectively embedded in the agenda and valuable to the design process.

All participants stated that the Studio provided them with a new perspective on living artefacts, introducing a method that could be integrated into their practice. However, they found the most engaging and motivating aspect to be the topic itself, so working with this type of artefact. This insight led organizers to reconsider whether the Understanding, Exploring, and Applying framework is fully suitable for a one-day workshop format.

7.6 Conclusion: shaping *soft* living artefacts

This chapter explored the emerging field of Engineered Living Materials (ELMs) and their potential to act as soft robots for designing in the context of intimate and bodily interaction. The Studio, conducted during the TEI 25 Conference, demonstrated the promise of *augmenting* everyday artefacts with living materials to improve their user experience, usability, and adaptability. By applying augmented silicone – a material with life-like qualities such as self-regeneration and environmental responsiveness – participants were able to reimagine the functionality and design of three artefacts: dual-use sex toy, menstrual cup, and breast pump. These artefacts pose user experience challenges, and they can benefit from the enhanced properties of ELMs, leading to more personalized, comfortable, and sustainable solutions.

The results of the Studio highlighted the interdisciplinary nature of such explorations, where design, synthetic biology, and HCI intersect to create novel and engaging user experiences. Despite the promising outcomes, the exploration of ELMs in design raises important ethical considerations, particularly regarding the integration of such living materials into everyday products. Issues the ethical implications of designing with living systems must be carefully addressed as this field continues to evolve.

As research continues to push the boundaries of materiality in design, the future holds compelling possibilities for more dynamic, responsive, and *soft* living artefacts that not only serve functional purposes but also foster more intimate interactions between people and bodily products.

Acknowledgement

The author would like to thank Professor Venere Ferraro, Professor Neel S. Joshi, and Valeria Regis for their support in co-organizing the Studio.

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8. Conclusions: the future of living artefacts and their application in made in Italy sectors

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Politecnico di Milano

As living artefacts become an *emerging reality*, their design requires new methodologies, tools, and ethical considerations. This book presents not only *a structured framework* but also *practical strategies* for working with *natural, engineered, and programmable living materials*. It presents a cohesive reflection based on findings from literature, practical examples across design, human-computer interaction, and biology, and ultimately three workshops with students and researchers. The book serves as a *call to action for designers, researchers, and industry professionals*, equipping them with *the tools and methodologies needed to transition toward a future where artefacts are not just sustainable – but truly alive in their interaction with humans.*

Livingness in design is a *transformative concept*, extending beyond the creation of objects to explore their lifecycle, adaptability, and ability to evolve in symbiosis with users and environments. The traditional boundaries between *material, organism, and technology* are dissolving, creating opportunities for designers to rethink *the agency of materials and artefacts*. Livingness, as proposed in this book, is not merely about integrating biological materials into everyday products but rather about creating *mutualistic relationships* where artefacts function as *co-evolving systems* that grow, regenerate, and adapt over time. The research in this book leverages both *natural and engineered biological materials and programmable matter*, positioning them within *new production and consumption models* that prioritize *circularity, biodegradability, and ecological intelligence.*

Designing with livingness requires an entirely new mindset, one that embraces uncertainty, adaptability, and interdisciplinary collaboration. As the field of living artefacts continues to grow, there is a pressing need for new material taxonomies, scalable fabrication techniques, and ethical guidelines that govern their implementation.

Three workshops conducted as part of this research demonstrated the potential of living artefacts in different design sectors of the Made in Italy system.

In yacht design, participants explored integrating *bioluminescent bacteria, responsive biofilms, and mycelium-based structures* in everyday objects and interiors. Findings emphasized that interactivity and adaptability are crucial in designing with livingness. Artefacts must respond to user behavior, environmental changes, and lifecycle transformations. Discussions centered on how interior spaces could become dynamic, breathing environments with materials that self-repair, purify air, or react to light and humidity, highlighting the potential of living artefacts to replace static, fossil-based materials in home and commercial spaces.

The second workshop, focused on cohabitation with living artefacts, explored *creating a living biofilter for water purification in kitchen environments.* Participants engaged in hands-on prototyping with an ad-hoc bacterial consortium , envisioning kitchens as active ecological interfaces. The project demonstrated how domestic spaces could integrate self-sustaining ecosystems that purify water, regulate humidity, and reduce waste. Results underscored that successful integration of living artefacts in homes requires user engagement and intuitive maintenance strategies.

The third workshop, *centered on biomedical design, investigated the potential of engineered living materials* in products designed for sensory and intimate interaction with the body . Participants engaged with an augmented silicone developed by synthetic biologists to envision new design possibilities leveraging the mechanical properties of soft robots based on the engineered living material. Results include self-healing materials, bio-sensing interfaces, and sustainable soft robots. Key takeaways highlighted the transformative potential of living materials in medical design, enabling responsive, adaptive and biocompatible artefacts. However, significant challenges remain, particularly in ethical oversight, regulatory approval, and scalable fabrication. Addressing these issues will require further research into standardized production processes, clinical trials, and responsible bioethics in medical-grade living materials.

These findings provide valuable insights into the future direction of research and practice in this field. By addressing the challenges of unpredictability, scalability, and ethical responsibility, designers and researchers can push the boundaries of what is possible with biodesign, synthetic biology, and responsive materials. Furthermore, the growing interest in cross-sector applications – from consumer products, fashion, and interior design to biomedical design – suggests that living artefacts will play an increasingly prominent role in shaping the future of the Made in Italy sectors.

As this field continues to develop, it will require ongoing *collaborations between scientists, engineers, designers, policymakers, and the public* to ensure that living artefacts are deployed in ways that are ethically sound, environmentally sustainable, and functionally viable. Future research must further explore how livingness can be integrated into mainstream manufacturing and consumer culture, how users interact with and perceive living materials, and how these materials can be optimized for longevity, performance, and ecological balance.

Ultimately, the future of livingness in design represents a paradigm shift that transcends material innovation, positioning designers not only as creators but as caretakers of material ecosystems. This new era of material agency challenges traditional notions of permanence and control, encouraging a more adaptive, symbiotic, and ecologically integrated approach to design. The workshops *provided tangible proof that livingness is not just a theoretical concept but a viable and transformative approach to design*, one that has the potential to reshape industries, redefine the boundaries of material innovation, and portray compelling novel user interactions. This book serves as both a blueprint and a provocation, urging designers to rethink their role – not just in shaping artefacts, but in shaping futures that are regenerative, adaptive, and truly alive.

As living artefacts become an emerging reality, their design requires *new methodologies, tools, and ethical considerations*. This book presents not only *a structured framework* but also *practical strategies* for working with *natural, engineered, and programmable living materials*. It serves as a *call to action for designers, researchers, and industry professionals*, equipping them with the *tools and methodologies needed* to transition toward a future where artefacts are not just sustainable – but *truly alive*.

Annex I

Case studies card, Chapter 2

#living #bioluminescent micro-organisms #bacteria

Ambio

Teresa Van Dongen, 2014

A swinging lamp filled with bioluminescent micro-organisms that emit light when provided with oxygen

HOW IT ACTS/INTERACTS: EMITTING LIGHT (BLUE)
HOW IT IS DEVELOPED: BIOLUMINESCENT MICRO-ORGANISMS' CULTURING (IN ARTIFICIAL SEA WATER)

// sector: PRODUCT

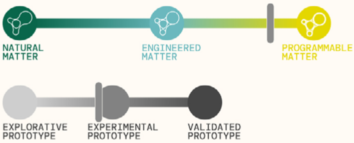
#soft robots

AMPHIBIO

Jun Kamei, 2018

3D printed amphibious garment supports underwater breathing by replenishing oxygen from the surrounding water and dissipating carbon dioxide which accumulate in the system (It doesn't work well enough for the breathing needs of a human being)

HOW IT ACTS/INTERACTS: BREATHING UNDER WATER
HOW IT IS DEVELOPED: SOFT ROBOTICS, 3D PRINTING, TISSUE-MIMICKING



// sector: PRODUCT

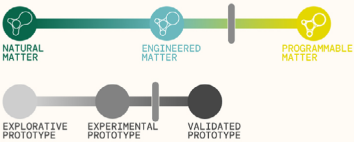
#living #bacteria

Bacterial Biocement

Laura Maria Gonzalez, 2023

Bricks fabricated by bacteria added to sand and placed in molds, fed with nutrients and naturally hardened

HOW IT ACTS/INTERACTS: CREATION OF THE MATERIAL ITSELF, SELF-HEALING
HOW IT IS DEVELOPED: BIOMINERALITATION, BIOFABRICATION



// sector: PRODUCT

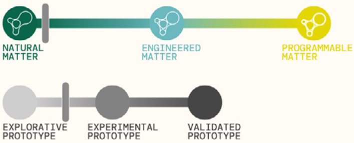
#living #plants

beGrounded

Lara Campos, 2018

Growing garment through embedded seeds into yarn, and digitally fabricated kit to recreate the garment

HOW IT ACTS/INTERACTS: /PROVOCATION
HOW IT IS DEVELOPED: GROWING DESIGN PROCESSES (EMBEDDED SEEDS INTO YARN), DIY METHODS, TEXTILE TECHNIQUES



// sector: FASHION

#living #algae

Biocatalytic cell

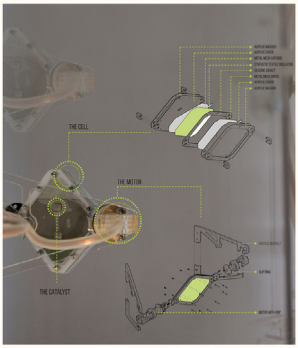
Thora H Arnardottir, Jessica Dias & Christopher Wong, 2022

Adapting a biophotovoltaic film system to create an adaptive energy-producing algae cell, harnessing this microorganism's ability to generate electricity via the photosynthesis process

HOW IT ACTS/INTERACTS: ELECTRICITY GENERATION
HOW IT IS DEVELOPED: ELECTRO-BIOFABRICATION, ALGAE'S CULTURING

NATURAL MATTER — ENGINEERED MATTER — PROGRAMMABLE MATTER

EXPLORATIVE PROTOTYPE — EXPERIMENTAL PROTOTYPE — VALIDATED PROTOTYPE



// sector: PRODUCT

#living #algae

Biogarmentry

Roya Aghighi, 2019

A fabric made by *chlamydomonas reinhardtii*, a type of single-cell green algae spunned together with nano polymers. It is a non woven living and photosynthetic textile

HOW IT ACTS/INTERACTS: SPECULATION, AIR PURIFICATION
HOW IT IS DEVELOPED: BIOFABRICATION, BIOHYBRIDIZATION PROCESSES

NATURAL MATTER — ENGINEERED MATTER — PROGRAMMABLE MATTER

EXPLORATIVE PROTOTYPE — EXPERIMENTAL PROTOTYPE — VALIDATED PROTOTYPE

// sector: FASHION

#living #protein #bacteria

Biofilm Integrated Nanofiber Display (BIND)

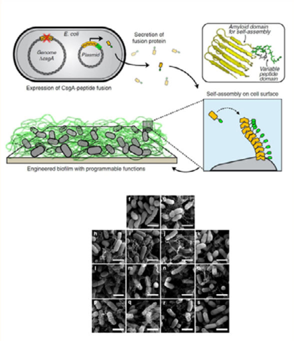
The Joshi Lab, 2019-ongoing

The technology leverages the natural fiber-producing capabilities of E. coli and enhances them to create advanced materials with unique and useful properties.

HOW IT ACTS/INTERACTS: CREATING FIBERS WITH NEW PROPERTIES
HOW IT IS DEVELOPED: PROTEIN ENGINEERING, BIOENGINEERING PROCESSES

NATURAL MATTER — ENGINEERED MATTER — PROGRAMMABLE MATTER

EXPLORATIVE PROTOTYPE — EXPERIMENTAL PROTOTYPE — VALIDATED PROTOTYPE



// sector: BIOTECHNOLOGY

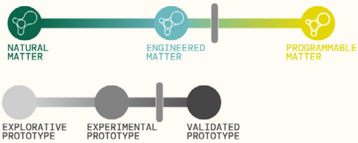
#living #bacteria

bioLogic

MIT Media Lab &
Tangible Media Group, 2015

Self-transforming biological skin activated by living bacteria. The synthetic bio-skin reacts to body heat and sweat

HOW IT ACTS/INTERACTS: SHAPE-CHANGING
HOW IT IS DEVELOPED: BACTERIA'S CULTURING, BIOHYBRIDIZATION PROCESSES, DIGITAL MANUFACTURING OF LIVING MATERIALS,BIO-PRINTING



// sector: FASHION-INTERACTION

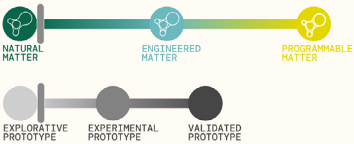
#biophilia

Biophilic Super Yacht

design studio 3deluxe, 2021

Visionary, nature-oriented philosophy of the project: light-suffused, loft-like space forms a spacious room continuum made up of a greenhouse, lounge living space, and vegetable garden. Luxury is rewritten entirely, with natural surroundings.

HOW IT ACTS/INTERACTS: ///
HOW IT IS DEVELOPED: ///



// sector: YACHT

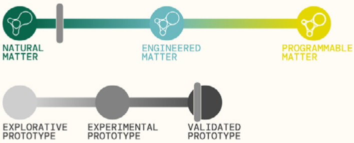
#living #bacteria

Breathing Shoe

PUMA + MIT Design Lab, 2018-2021

A shoe patterned with microorganisms which respond to the heat generated by the feet and proliferate by consuming the media in the cavities, giving a custom look based on the activity profile of their users

HOW IT ACTS/INTERACTS: COSTUMIZE ITS SHAPE (ON USER NEEDS)
HOW IT IS DEVELOPED: BACTERIA'S CULTURING, BIOHYBRIDIZATION PROCESSES, DIGITAL MANUFACTURING OF LIVING MATERIALS



// sector: FASHION

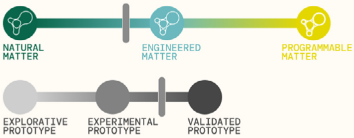
#living #interactive #bacteria

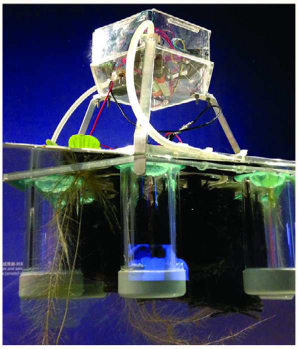
Caravel

Ivan Henriques, 2016

Self-sustaining environmental robot that cleans water harvesting energy through bacteria

HOW IT ACTS/INTERACTS: WATER PURIFICATION, ELECTRICITY GENERATION
HOW IT IS DEVELOPED: ELECTRO-BIOFABRICATION, BACTERIA'S CULTURING





// sector: INTERACTION-PRODUCT

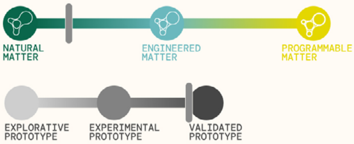
#living #mycrobes

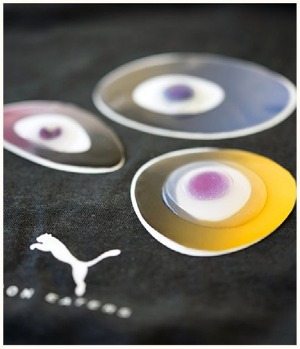
Carbon Eaters

PUMA + MIT Design Lab, 2018

Microbially-activated color-changing stickers for inform about the air quality

HOW IT ACTS/INTERACTS: COLOUR CHANGING (FEEDBACK)
HOW IT IS DEVELOPED: MICROBES'S CULTURING, BIOHYBRIDIZATION PROCESSES, DIGITAL MANUFACTURING OF LIVING MATERIALS





// sector: FASHION

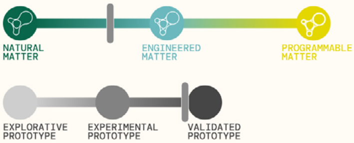
#living #bacteria

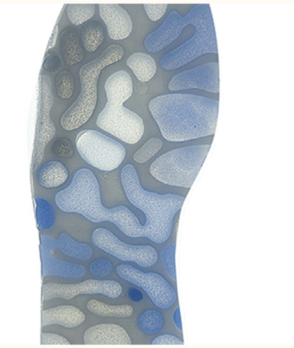
Deep Learning Insole

PUMA + MIT Design Lab, 2018

Insoles that contain microbial cultures to monitor biochemical vitals, responding to the skin and sweat, digitizing the biochemical signals and providing the user with benchmarks to optimize their performance

HOW IT ACTS/INTERACTS: GIVING FEEDBACK ON USER'S PERFORMANCE
HOW IT IS DEVELOPED: BACTERIA'S CULTURING, BIOHYBRIDIZATION PROCESSES, PROGRAMMING





// sector: PRODUCT-FASHION-INTERACTION

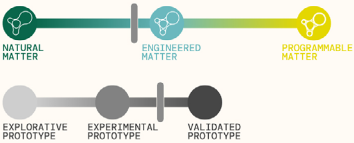
#living #bacteria #protein

Electric skin

Nada Elkharashi, Catherine Euale, Sequoia Fischer & Paige Perillat-Piratoine, 2022-current

Biomaterial device that can generate electricity, using the protein nanowires from Geobacter Sulfurreducens.

HOW IT ACTS/INTERACTS: EMITTING LIGHT, ELECTRICITY GENERATION
HOW IT IS DEVELOPED: PROTEIN ENGINEERING, BIOHYBRIDIZATION PROCESSES, ELECTRO-BIOFABRICATION



// sector: PRODUCT-INTERACTION

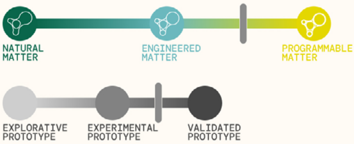
#living #bacteria

E. chromi: Living Colour from Bacteria

ALEXANDRA DAISY GINSBERG AND JAMES KING, 2009

Engineered bacteria, ingested in yoghurt, would colonise human's gut, keeping watch for the chemical markers of diseases. If disease is detected, the bacteria produce an easy-to-read warning by colouring the poo.

HOW IT ACTS/INTERACTS: COLOUR CHANGING (FEEDBACK)
HOW IT IS DEVELOPED: BIOENGINEERING PROCESSES, SYNTHETIC BIOLOGY



// sector: HEALTH

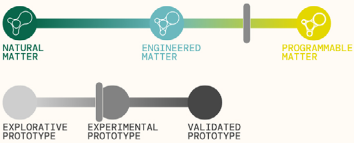
#living #bacteria

Flexible and Stretchable Biobatteries

Sumiao Pang, Yang Gao & Seokheun Cho, 2017

Textile-based, bacteria-powered biobattery that could be integrated into wearable electronics and fed with sweat generated from the human body

HOW IT ACTS/INTERACTS: ELECTRICITY GENERATION (FROM SWEAT)
HOW IT IS DEVELOPED: PROGRAMMING, ELECTRO-BIOFABRICATION



// sector: FASHION

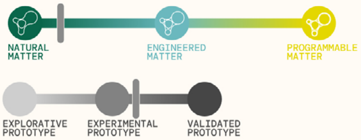
#living #bacteria

Future Flora

Giulia Tomasello, ALMA, 2018-ongoing

A speculative harvesting kit designed for people with vagina to treat and prevent vaginal infections. The bacterial pad creates a hostile environment for the further development of Candida

HOW IT ACTS/INTERACTS: PREVENTING AND TREATING VAGINAL INFECTION
HOW IT IS DEVELOPED: BACTERIA'S CULTURING, BIOFABRICATION, DIY METHODS



// sector: FASHION-HEALTH

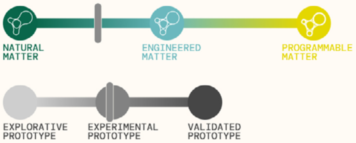
#living #mycelium

Fungi Mutarium

Livin Studio
& Utrecht University, 2014

A prototype that grows edible fungal biomass, mainly the mycelium, with agar, starch and sugar, as a novel food product that digests (plastic) waste

HOW IT ACTS/INTERACTS: PLASTIC DIGESTION, FOOD PRODUCING
HOW IT IS DEVELOPED: GROWING DESIGN PROCESSES, LAB EXPERIMENTATION, DIGITAL BIOFABRICATION



// sector: PRODUCT

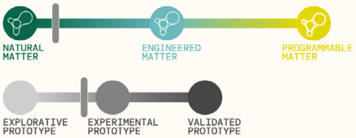
#living #lichens

Grow Your Own Couture

Piero D'Angelo, 2023

Fashion garments integrating lichens to absorb air pollutants, delivered in a DIY kit

HOW IT ACTS/INTERACTS: AIR PURIFICATION
HOW IT IS DEVELOPED: GROWING DESIGN PROCESSES, BIOFABRICATION, DIY METHODS



// sector: FASHION

#living #algae

Grown Blur

Boqun Huang, 2023

Dyeing of micro-algae by cultivating them directly on the fibers with the traditional weaving technique

HOW IT ACTS/INTERACTS: COLOURING
HOW IT IS DEVELOPED: TEXTILE TECHNIQUES, ALGAE'S CULTURING, BIOFABRICATION

// sector: FASHION

#living #mycelium

Gunya MYC_Couture 04

Dasha Tsapenko, 2024

A typical Ukrainian mud hut made with raw compressed hemp and sawdust bonded together with mycelium and clay. It is very efficient in thermoregulation

HOW IT ACTS/INTERACTS: WARMTH PROVIDING, INSULATION
HOW IT IS DEVELOPED: BIOFABRICATION, GROWING DESIGN PROCESSES

// sector: FASHION

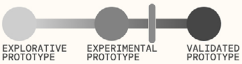
#living #bacteria

H.O.R.T.U.S. XL

ecoLogicStudio & Synthetic Landscape Lab, 2019

3D printed bio-sculpture inhabited by cyanobacteria, receptive to both human and non-human life, powered by photosynthesis, convert radiation into actual oxygen and biomass

HOW IT ACTS/INTERACTS: SPECULATION, AIR PURIFICATION
HOW IT IS DEVELOPED: 3D PRINTING, COMPUTATIONAL DESIGN, BACTERIA'S CULTURING



// sector: PRODUCT-ARCHITECTURE

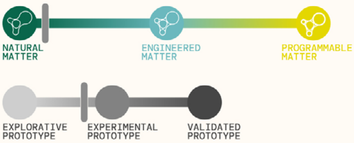
#living #plants

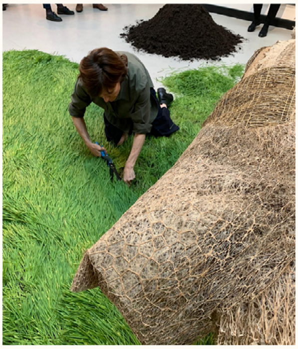
Interwoven

Diana Scherer, 2015-ongoing

Plant root system domestication through intricate pattern inspired by the forms of the xylem vessels in plant anatomy

HOW IT ACTS/INTERACTS: SPECULATION
HOW IT IS DEVELOPED: GROWING DESIGN PROCESS, DIGITAL BIOFABRICATION, COMPUTATIONAL DESIGN





// sector: PRODUCT-ART

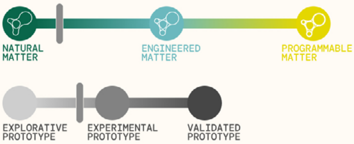
#living #plants

Interwoven - Biodigital objects

Jiwei Zhou, 2020

Low stool grown by roots, connecting 600 hollow, parametrically optimized porous beads

HOW IT ACTS/INTERACTS: CO-CREATION OF THE MATERIAL ITSELF, GLUEING
HOW IT IS DEVELOPED: TINKERING, 3D PRINTING, DIGITAL BIOFABRICATION, COMPUTATIONAL DESIGN



// sector: PRODUCT

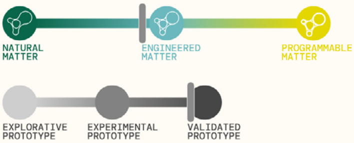
#living #algae

LIQUID 3

University of Belgrade - Institute for Multidisciplinary Research, 2023

Microalgae tank for air purification in urban centers (10 to 50 times more efficient than a tree)

HOW IT ACTS/INTERACTS: AIR PURIFICATION
HOW IT IS DEVELOPED: ALGAE'S CULTURING IN BIOREACTORS



// sector: PRODUCT-ARCHITECTURE

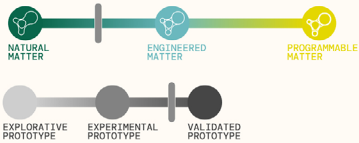
#living #plants #bacteria #prototype

Living Light

Ermi van Oers, Nova Innova & Plant-e, 2017

Lamp harvesting energy through the photosynthetic process of plants and metabolism of bacteria

HOW IT ACTS/INTERACTS: EMITTING LIGHT
HOW IT IS DEVELOPED: ELECTRO-BIOFABRICATION



// sector: PRODUCT

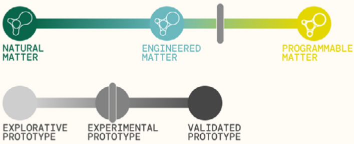
#living #interactive #bacteria

Living Tattoo

Xinyue Liu & MIT, 2017

3D printed living tattoo made of bacterial-based hydrogel ink sensitive to a different chemical or molecular compound

HOW IT ACTS/INTERACTS: COLOURING (FEEDBACK)
HOW IT IS DEVELOPED: 3D PRINTING, GENETICAL PROGRAMMING OF BACTERIA, BIO-INGENEERING PROCESSES, PROTEIN ENGINEERING



// sector: INTERACTION-FASHION

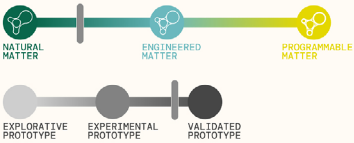
#living #algae

Living Things

Jacob Douenias, Ethan Frier & Lena Tesone, 2016

Interior lighting installation incorporating microalgae that produces oxygen, food, and fuel through photosynthesis

HOW IT ACTS/INTERACTS: EMITTING LIGHT, HEATING, FOOD PRODUCING
HOW IT IS DEVELOPED: ALGAE'S CULTURING IN BIOREACTORS



// sector: PRODUCT

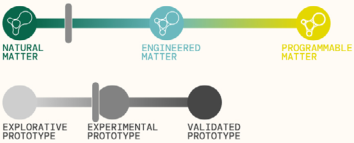
#living #bacteria

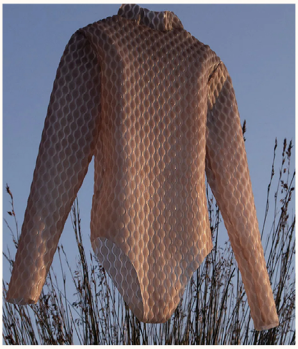
MELWEAR

Maca Barrera, 2023

Harnessing the power of microbes (bacterial melanin) to produce a natural derived sunscreen that shield the body from harmful UV radiation. It becomes gradually darker when the user is exposed to UV rays

HOW IT ACTS/INTERACTS: UV PROTECTION, COLOR CHANGING (FEEDBACK)
HOW IT IS DEVELOPED: SPECULATION, BACTERIA'S CULTURING





// sector: FASHION-HEALTH

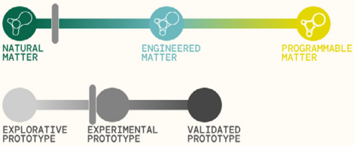
#living #microbes

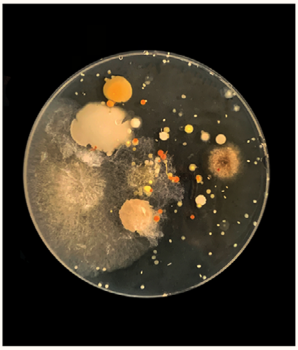
μMe

Fiona Bell, Michelle Ramsahoye, Joshua Coffie, Julia Tung & Mirela Alistar, 2021-2024

Skin microbiome as an intimate material for designing living interfaces of daily activities and body parts

HOW IT ACTS/INTERACTS: COLORING
HOW IT IS DEVELOPED: CULTURING SKIN'S MICROBIOME, GROWING DESIGN PROCESS





// sector: FASHION

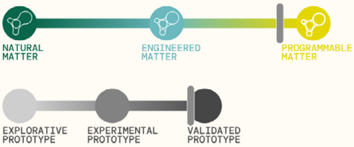
#nylon #fiber

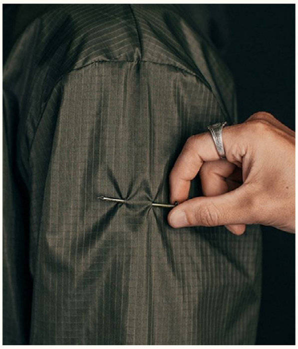
Nano Cure Tech - Nylon fabric

Imperial Motion, 2018

Water-resistant nylon material having capabilities of self-reparation (through double side pressure and finger heat)

HOW IT ACTS/INTERACTS: SELF-HEALING
HOW IT IS DEVELOPED: NANOTECHNOLOGIES, TEXTILE TECHNIQUES





// sector: FASHION

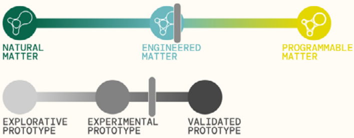
#living #plancton

Phyto Printing

Luis Undritz, 2021

Phyto printing uses a light projection to control the growth of phytoplankton to create high-resolution prints. The result is a living material that breathes and metabolises

HOW IT ACTS/INTERACTS: COLOURING, AIR PURIFICATION
HOW IT IS DEVELOPED: SCREENPRINTING PROCESS(DLP LASER PROJECTOR), BIOFABRICATION PROCESS



// sector: FASHION

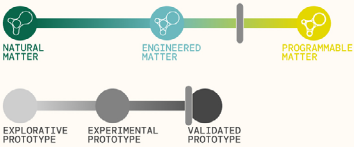
#living #bacteria

Plug-and-play modular biobatteries

Anwar Elhadad, Lin Liu & Seokheun Choi, 2022

A microfabricable and scalable biobattery that includes a microbial consortium. 3 layers of different types of bacteria cooperate to generate electricity

HOW IT ACTS/INTERACTS: ELECTRICITY GENERATION
HOW IT IS DEVELOPED: PROGRAMMING, ELECTRO-BIOFABRICATION, ELECTROPOLYMERIZATION



// sector: PRODUCT

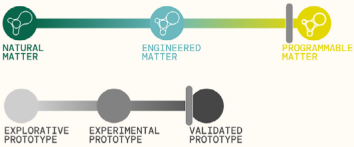
#soft robots

SELK's programmable textile actuators

MotorSkins, 2023-ongoing

Multilayered textile structure exemplifies programmable matter, endowing it with the ability to sense, react, and adapt to its surroundings

HOW IT ACTS/INTERACTS: ADAPTATION, PHYSICAL REACTION, MOVEMENT
HOW IT IS DEVELOPED: SOFT ROBOTICS, FLUID LOGIC, PROGRAMMING, BIO-INSPIRED DESIGN, TISSUE MIMICKING



// sector: INTERACTION-FASHION

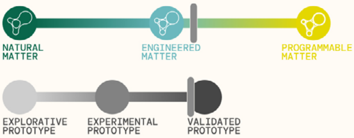
#living #bacteria

Skin II

Rosie Broadhead, 2021-2022

Encapsulated probiotic bacteria in key areas into the fibres of clothing. They activate when they come into contact with the moisture on our skin, they are associated with reduced body odour, encouraging cell renewal, and improving the skin's immune system

HOW IT ACTS/INTERACTS: REDUCING ODOUR, CELL RENEWAL,IMPROVING IMMUNE SYSTEM
HOW IT IS DEVELOPED: TEXTILE TECHNIQUES, BACTERIA'S CULTURING, BIOFABRICATION



// sector: FASHION-HEALTH

#living #slime mold

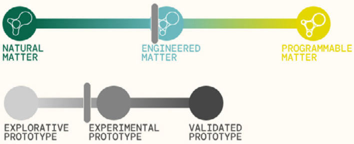
Smartwatch slime mold

Integrating Living Organisms in Devices to ImplementCare-based Interactions

Jasmine Lu & Pedro Lopes, 2022

Researchers engineered a smartwatch that includes a slime mold that physically conducts power to a heart rate sensor inside the device, acting as a living wire

HOW IT ACTS/INTERACTS: DATA VISUALIZING
HOW IT IS DEVELOPED: PROGRAMMING, ELECTRO-BIOFABRICATION, MOLD'S CULTURING



// sector: PRODUCT-MATERIAL

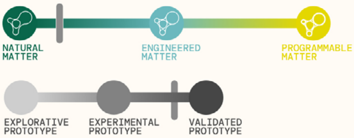
#living #bacteria

Spark of Life

Teresa Van Dongen, 2016

Electrochemically active bacterias emit light and generate electricity into the "living lamp"

HOW IT ACTS/INTERACTS: EMITTING LIGHT
HOW IT IS DEVELOPED: BACTERIA'S CULTURING



// sector: PRODUCT

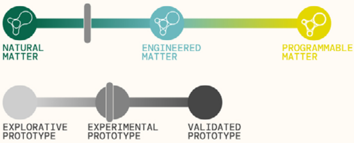
#living #algae #bacteria

The Soothing Cup

Lucrezia Alessandroni, 2022

The development of an algae-based hydrogel mixed with lactobacillus allows the menstrual cup to become a membrane able to interact with the vaginal environment

HOW IT ACTS/INTERACTS: BALANCING VAGINAL MICROBIOMA
HOW IT IS DEVELOPED: 3D PRINTING, CASTING PROCESSES, BACTERIA'S CULTURING



// sector: PRODUCT-MATERIAL

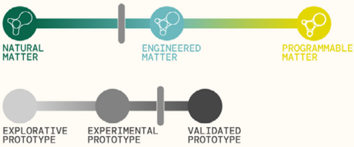
#living #slime mold

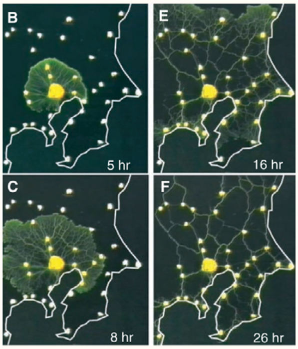
Tokyo rail system

Atsushi Tero et al., 2010

Slime mould Physarum polycephalum solves a network design problem by maximising transport capacity and minimising the size and length of the network

HOW IT ACTS/INTERACTS: NETWORK DESIGN SOLVING
HOW IT IS DEVELOPED: SLIME MOULD'S CULTURING, PROGRAMMING, BIOHYBRIDIZATION PROCESSES, COMPUTATIONAL DESIGN





// sector: URBANISTIC-ARCHITECTURE

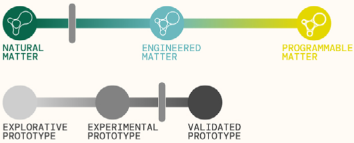
#living #algae

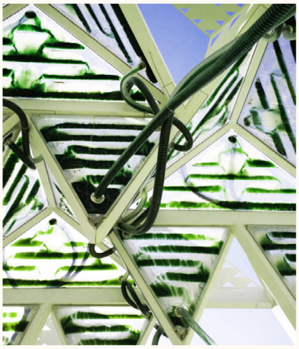
Urban Algae Folly

ecoLogicStudio, 2015

Interactive pavilion with living micro-algal cultures that absorb air-pollutant. The visitors can interact with the structure with their smart phones

HOW IT ACTS/INTERACTS: AIR PURIFICATION
HOW IT IS DEVELOPED: ALGAE'S CULTURING IN BIOREACTORS





// sector: PRODUCT-ARCHITECTURE

#living #interactive #bacteria

Vespers III

Neri Oxman & MIT, 2018

Living mask embodying habitats that induce engineered bacteria to produce pigment in response to detected chemicals

HOW IT ACTS/INTERACTS: SPECULATION, COLOURING (FEEDBACK)
HOW IT IS DEVELOPED: 3D PRINTING BIOACTIVE MATERIALS, BACTERIA'S CULTURING, BIOHYBRIDIZATION PROCESSES

NATURAL MATTER — ENGINEERED MATTER — PROGRAMMABLE MATTER

EXPLORATIVE PROTOTYPE — EXPERIMENTAL PROTOTYPE — VALIDATED PROTOTYPE

// sector: FASHION-INTERACTION

#living #bacteria #edible plants

Zero_Mile system

Dipartimento di Design - Polimi
Dipartimento di Biologia - Tor Vergata, 2018-ongoing

Interdisciplinary research project that aims to reuse dishwater wastewater to grow vegetables and/or ornamental plants for domestic use by an engineered biological filter integrated into a prototype.

HOW IT ACTS/INTERACTS: WASTEWATER TREATEMENTS
HOW IT IS DEVELOPED: BACTERIA'S CULTURING

NATURAL MATTER — ENGINEERED MATTER — PROGRAMMABLE MATTER

EXPLORATIVE PROTOTYPE — EXPERIMENTAL PROTOTYPE — VALIDATED PROTOTYPE

// sector: PRODUCT

#living #yeast #bacteria

Adaptive Packaging

PUMA + MIT Design Lab, 2018

Package that contains two types of microorganisms; yeast which produces CO2 to inflate the air sacks and bacteria to deflate them over time by degrading the material

HOW IT ACTS/INTERACTS: INFLATION (AIR SACKS), SHAPE ADAPTATION
HOW IT IS DEVELOPED: BIOFABRICATION, BACTERIA'S AND YEAST'S CULTURING

NATURAL MATTER — ENGINEERED MATTER — PROGRAMMABLE MATTER

EXPLORATIVE PROTOTYPE — EXPERIMENTAL PROTOTYPE — VALIDATED PROTOTYPE

// sector: PRODUCT

Annex II

Final outcomes of the workshop, Chapter 6

HALO

Team 01

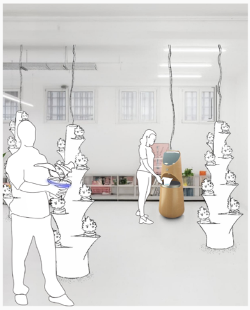
Caffo Erika, Nicolini Alessia, Spinas Niccolò, Taheir Duha, Topada Tugce

Context

A design studio based in Milan comprises a team of 15-20 dynamic creatives. The studio operates in a co-working environment with a strong visual identity. The space is currently characterized by a cold atmosphere and a lack of natural light. For this reason, the project aims to design a relaxation area within the office, integrating a biofilter and several plant totems. The goal was to transform a white environment into a more vibrant space, providing workers a place to recharge and connect with nature.

Biofilter

The biofilter is contained in a totem located inside the breakout room. The totem connects the biofilter, with its internal consortium, to a water dispenser from which workers can take it to irrigate the plants. Additionally, the system is automatically connected to other totems with plants to water them. The biofilter is a cylinder with an irregular base made from a transparent material to make the consortium inside visible. A light placed underneath the biofilter illuminates the system and keeps the organisms alive while facilitating communication with the users.



LIFE / Living Integrated Filtration Ecosystem

Team 02

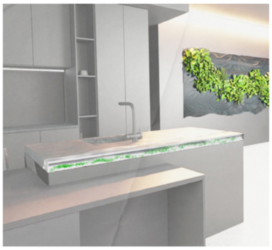
Chiara Andreiuolo, Ottavia Griesi, Yufan Liu, Lantian Liang

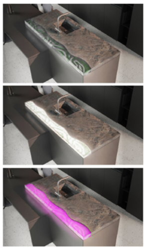
Context

A young, tech-savvy couple passionate about sustainability. They care for the biofilter, maintain the indoor garden and harvest vegetables. The biofilter is integrated into the kitchen countertop and serves as a practical appliance and a design feature.

Biofilter

The biofilter is a blend of sustainability, technology, and design seamlessly integrated into the kitchen. It offers functionality and aesthetics, with light cues that signal its status, naturally fitting into the home's rhythm.





mizu

Team 03

Zülal Yaşar, Ekin Kaptan, Tanishka Kadam, Dilara Tanrıöven, Xinyu Wang

Context

An apartment for five students with five bedrooms and a small kitchen. The dishwasher is at the end of the kitchen, adjacent to the balcony. The dishwasher in the kitchen is used once a day throughout the week. Each flatmate takes responsibility for the biofilter system according to turns. The system use is private to the household, and the biofilter and cultivation are outdoors on the balcony.

Biofilter

The biofilter is a system of 6 glass modules that work in cycles based on the use of the dishwasher. Each module has a 6-litre capacity to accommodate the wastewater and allow space on top. Each module is 10 cm thick, and the height is 20 cm. The surface is 30 x 23 cm, ensuring easy management. The modules also have a metal casing with easy rails at the back for attachment to the panel on the balcony. It comes with a removable filter that helps extract excess of the consortium.

LUMEA

Team 04

Chunhan Yi, Divanshi Goel, Nicolàs Herrera-Posada, Oda Bentzen, Federico Denni

Context

Another hostel guest. The context is a renovated space in the middle of Bovisa. The place is an ex-milling place, then a parking spot. In 2021, the place was bought and renovated, becoming a co-working space with a restaurant and bar and, finally, a hostel. A social hub for the quarter where the plants that ornament the indoor space are the backdrop of musical events, talks, and live podcasts that the staff takes care of, keeping them healthy and hydrated.

Biofilter

Combining light, color, and simplicity, Lumea transforms water filtration into a decorative experience. Inside each biofilter, living bacteria actively purify the collected water. As these bacteria grow over time, they influence the light's appearance—when they flourish, the light takes on a natural green hue, making the illumination a reflection of the bacteria's life cycle. Each unit collects up to 10 liters of water, which is automatically repurposed for daily indoor plant irrigation. Its modular design allows each filter to function independently, making it ideal for businesses of any size. Smaller restaurants can start their sustainability journey with just one unit, taking meaningful steps toward eco-conscious operations.

BioWave

Team 05

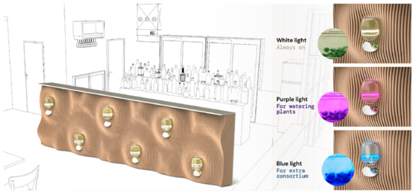
Lucrezia Argentieri, Beyza Artunc, Cinar Aysun, Giulia Grimaz, Turkoz Iklima Iklima

Context

The context is a vibrant hybrid space combining a restaurant, hotel, and café. With an indoor biofilter and integrated cultivation, the staff cares for the garden while guests work and connect, creating a collaborative, eco-conscious atmosphere.

Biofilter

The biofilter at the counter uses lights and sounds to communicate its health status to workers. Its signals capture customers' attention, prompting them to approach and discover the biofilter through a magnifier mirror, creating an engaging and informative interaction between the environment and visitors.



FERNIE

Team 06

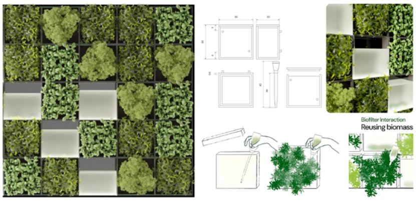
Arianna Bardelli, Guanjun Yu, Lucia Medina, Michela Pace, Xinyu Liu

Context

Fernie is a modular wall system designed for restaurants that want to reduce their environmental impact. The biofilters, filled with microbial consortiums, use lights to communicate with their users, resulting in an embodied interaction. This creates a relationship of care and reciprocating help between Fernie and the restaurant staff, thus ensuring appropriate health for the consortium. The module is visible to guests, contributing to their dining experience and making them aware of the ecological approach that is taking place.

Biofilter

Each UV-resistant polycarbonate biofilter offers durability, light transmission, heat insulation, and alcohol resistance for easy cleaning. An automatic lighting system adjusts illumination, while a temperature sensor changes light color to signal unsafe water temperatures. A custom app manages irrigation, monitors data, and sends cleaning reminders. To remove and instantly reuse the biomass, each biofilter comes with a large pipette to suck up the excess and replant it in the nearby plant pots, fertilizing them.



ECO FLOW

Team 07

Yixuan Ren, Kangyu Zhao, Chi Zhu, Razieh Soleimani

Context

The context is a modern family that cares about sustainability, efficiency, and aesthetics. The system is integrated into the interior patio of the house, providing an eco-friendly solution for recycling wastewater while enhancing the beauty of the living space.

Biofilter

The biofilter is an innovative, eco-friendly water filtration system designed to recycle wastewater from household dishwashing, transforming it into clean water for irrigation. The proposed solution is integrated with smart monitoring technology and ensures efficient water usage, reducing waste while promoting a sustainable lifestyle.

POLIGREEN - Co-Working in POLIMI Kitchen

Team 08

Gürsoy Cansel, Li Xinying, Montini Silvia, Song Zhuoyue, Spedicato Laura

Context

The context is the Design Department's kitchen space. The project aims to improve air quality and sustainability and create a more comfortable and welcoming space for the staff. Both the biofilter and the cultivation are located indoors so that the staff can collectively take care of the system and enjoy a relaxing time.

Biofilter

The biofilter purifies dishwasher wastewater to provide clean water for plants. It is semi-automatic, with sensors monitoring the consortium. Staff can check its status visually or through indicator lights and signaling issues. The user can partially remove the consortium by rotating the container and dispensing the mixture. Wall plants are automatically irrigated, while others require manual care. The minimalist, industrial-style container ensures seamless integration with the room's design.

Authors

Annamaria Alabiso: PhD in Evolutionary Biology and Ecology at the University of Rome Tor Vergata. The PhD project focuses on the development and implementation of the Zero Mile System biofilter, a microbial consortium specifically engineered for recycling and scaling up dishwasher wastewater. She is also conducting studies on the degradation of ancient parchments caused by biological and micro-biological factors to enhance the understanding of the ecological dynamics underlying biodeterioration.

Elena Albergati: PhD candidate in Design at Politecnico di Milano, part of the Materials Design for Transition research group and specialized in the intersection of Design and Bioengineering. Her research explores the potential of creating regenerative products and materials using living organisms, such as fungi, algae, and bacteria. Driven by a fascination with the possibilities of interactive design with living matter, Elena investigates methods for developing products in collaboration with biological systems. To support designers in this emerging field, she has developed a comprehensive set of maps and tools known as *Bio-UX*. This resource aims to guide researchers in integrating living organisms within design practices, advancing the field of Biological Interaction Design.

Lucrezia Alessandroni: Biodesigner driven by a passion for merging design principles with scientific inquiry. Her work explores the intersection of biology, technology, and design, particularly in the context of sustainability. In her projects, she investigates the relationship between scent and microbes, reimagines menstruation through microbial interaction, and examines food and ecosystems. She has led several lectures and workshops on designing and prototyping biomaterials, exploring bioprinting techniques and DIY approaches to lab work. Currently, a PhD researcher at the Living System Lab at Central Saint Martins, UAL, Lucrezia, has experience working as a Visiting Practitioner at MA Biodesign and as a Fermentation Technician at WinWin Food Labs. Her work has received awards, including a special mention at the RoPlastic Prize, and has been featured in magazines such as Dezeen and exhibited at events like Dutch Design Week and Milan Design Week.

Arianna Bionda: Senior Researcher and Professor at Politecnico di Milano, PhD in Design, Architect, Sailor and Yacht Designer. She is involved in research and teaching activities within the Yacht Design and Vessel Design group and the SMaRT Lab, focusing on nautical innovative technologies, materials and interaction practices. She contributes to projects on Yacht Design Digitalization and Design for Sustainability: Industry 4.0; Digital Technologies Onboard; Smart Shipbuilding; Design for Sustainable Material and Technology; Alternative Fuel Vessel Design; Design for Circular Economy, Disassembly and Recycling; Sustainable Social Innovation and Business Model; Design4all. She is Vice-Director of the Yacht Design Specialized Master, Director of the Executive Interior Yacht Design course and Project Manager of the Polimi Sailing Team.

Giorgia Burzio: PhD candidate at the Department of Design, Politecnico di Milano. Trained as product designer, she holds an MFA in Design from Konstfack University (Stockholm, Sweden), where she explored the agency of metals and silicones contained in electronic devices through a craft-oriented approach. Prior to her current studies, she worked as a Research Fellow at D\Tank, the think tank of the Department of Design at Polimi, and she was an artist-in-residence at Fabrica Research Centre. Her research focuses on the interplay between materials and intimate data, exploring how data can be critically treated as a material to design embodied interactions, supporting the sensemaking of digitized information and decision-making.

Valerio Cantelmo: Research fellow at the University of Rome Tor Vergata. He conducts research within the project *Upcycling of Microfibers into Nanodiamonds*, which focuses on a washing machine wastewater treatment system that includes the upcycling of synthetic microfibers into nanodiamonds. His role in this project involves developing an ad-hoc microbial consortium for the remediation of washing machine effluents. Additionally, he collaborates in the Zero Mile project, which aims to develop a biofiltration system for the treatment of dishwasher wastewater.

Giovanni Maria Conti: PhD cum laude, Associate Professor, is currently the Head of the Fashion Design Program at Politecnico di Milano. Scientific Coordinator of the KnitDesign Research Group at Design Department of Politecnico di Milano, he is an expert collaborator of the Instituto Italo-Latino Americano – IILA in the Pymes Forum for cooperation projects on textile and fashion. He is a member of the editorial board of *Lupetti. Editori di Comunicazione* and in 2020 he received the Honorable Mention at the XXVI Compasso d'Oro for the *DigiKnit* research. He is member of the Advisory Board of CiAUD, Research Center in Architecture, Urbanism and Design - Lisbon School of Architecture and member of LeNS - International Learning Network on Sustainability.

Fiammetta Costa: PhD in Industrial Design and Associated Professor at the Design Department of Politecnico di Milano. Her research focuses on user research and environmental design. Since 2000, she has taught Ergonomics and Industrial Design, currently holding the MSc Course in Interaction Technologies and Sustainable Development. She has coordinated research projects funded by the Italian

Ministry of University and technological research (MIUR) and participated in EU-funded initiatives. She served as President of the Unified Guarantee Committee and is involved in organizing the Digital and Interaction Design MSc. She has published over 100 academic works.

Venere Ferraro: Associate Professor in the Department of Design at Politecnico di Milano, where she also earned her PhD in Design. She has been a visiting researcher at the University of New South Wales in Sydney and the Media Lab at the Massachusetts Institute of Technology (MIT). Throughout her career, she has coordinated the European project *DATEMATS* (KA2-2018) while currently, she is the Principal Investigator for the Horizon Europe projects *IN TRANSIT* and *OpenVerse*, and she also coordinates the national project *RELIVE: Designing Living Artefacts for Regenerative Futures*, funded by Politecnico di Milano. Within the Department, she is one of the coordinators of D\Tank, the think tank of the Department of Design. Her research focuses on interaction design, particularly the role of sensory technologies, smart materials, and big data in creating experiential systems for digital care, with a specific interest in strategies for influencing user behavior.

Nicla Guarino: PhD candidate at the Design Department of Politecnico di Milano. She holds a BSc in Fashion Design and an MS in Design for the Fashion System at Politecnico di Milano. Her research and practice adopt an interdisciplinary approach, aiming to develop regenerative solutions for contemporary production and consumption challenges by leveraging the dynamic and experiential impact of matter. Currently, she focuses on the development of emerging materials and technologies coming from the Biodesign field to reframe the domains of Wearables and Interaction Design, addressing the pressing issue of textile and electronic waste. In addition to her design work, she has cultivated experience in education as a teaching assistant and secondary school teacher, specialising in materials and textiles for Fashion and Design applications.

Matteo Meraviglia: architect and computational designer. He holds a Master degree in architecture at Politecnico di Milano, a postgraduate degree in Sustainable Territory and Architecture, and from 2023 he's a PhD candidates in Design. He has worked in international architecture and urban design studios in Milan and Cairo. Since 2009, he has collaborated on research projects at the Department of Design. He is tutor at Laboratorio di Progettazione Architettonica 2 and lecturer in the DigiSkills course at AIUC. His research is focused on Biophilic Design, Computational Design, and sustainable systems, inspired by biological and mathematical algorithm processes.

Luciana Migliore: Associate Professor of Ecology and Ecotoxicology at the University of Rome Tor Vergata and serves as the Coordinator of the Master's Degree Program in Conservation and Restoration of Cultural Heritage. Her scientific work focuses on both basic and applied ecology, employing biotechnological techniques for rehabilitating contaminated matrices and studying biodeterioration processes in ancient documents. She has coordinated research projects supported by national and international funding, published over 250 scientific papers and holds three patents.

Attilio Nebuloni: architect, PhD and confirmed researcher in architectural and urban design, at the Department of Design of the Politecnico di Milano, where he teaches Architectural Design. The main research topics are computational design, responsive morphologies, and the interaction between architecture and sustainability mediated by digital aspects. He has promoted and directed workshops and courses on digital design tools. From 2008 to 2018, he taught the Master in Sustainable Territory and Architecture. Author of numerous scientific publications related to Architectural and Urban Composition, he is a member of the editorial board of the series *Materiali di architettura e di urbanistica* for Mimesis Edizioni.

Valeria Regis: Research Fellow at the Department of Design, Politecnico di Milano. With a Master's Degree in Design & Engineering from the same institution, they focus on combining technology, sustainable materials, and product design to create inclusive and thoughtful solutions. Their academic journey includes international experiences in South Korea and Sweden, where they developed an understanding of global design approaches and methodologies. Their research interests center on increasing the visibility and inclusion of under-represented groups through the design of products that encourage meaningful shifts in everyday practices.

Ludovico Ruggiero: PhD candidate in Design at Politecnico di Milano, is a researcher in the Yacht Design and Vessel Design group and the LeNSLab research group. With a background in Naval and Nautical Design, his work focuses on integrating Life Cycle Design (LCD) principles into yacht design processes to advance sustainable innovation. His research explores circular economy strategies, design for disassembly and recycling, and the role of digitalisation in enhancing the environmental performance and efficiency of yacht design. In addition to his research, Ludovico serves as a teaching assistant for master's and bachelor's degree courses. His work bridges academic research and industry practice, fostering innovation and sustainability within the yacht design field.

This book presents the results of the FARB (*Fondo d'Ateneo per la Ricerca di Base*) research project RELIVE, conducted within the Department of Design of Politecnico di Milano. RELIVE aimed to explore and conceptualize a framework for designing living artefacts. The objectives of the research are the conceptualization of original theory regarding livingness and the exploration of design-oriented approaches to craft living artefacts using living materials and digital technologies.
The book includes contributions from researchers at the intersection of biology and design, as well as from Human-Computer Interaction (HCI), to highlight the livingness within across various disciplines. Additionally, it presents the results of three workshops—two conducted at the School of Design and a third held at an international conference with experts on the subject. Through literature and case studies analysis, the interdisciplinary approach of the research allowed the formulation of a new definition of *livingness* based on three levels of living materials. The book provides the basis for future explorations in the field of living artefacts, proposing approaches and methods to practitioners interested in exploring livingness within relevant sectors. Ultimately it offers research trajectories including practical applications to promote regenerative futures and user interaction based on mutual care.

FrancoAngeli
La passione per le conoscenze