Design Science

What is livingness? From natural matter to a programmable one

Venere Ferraro, Giorgia Burzio and Nicla Guarino

Department of Design, Politecnico di Milano, Milan, Italy

Abstract

This article investigates "livingness" at the convergence of design, human–computer interaction (HCI) and synthetic biology, emphasising the evolving role of materialism. It examines living artefacts – objects designed with life-like qualities that utilise natural, engineered or programmable materials. The study thoroughly reviews theoretical underpinnings, highlighting new materialism's focus on the agency of matter and HCI's material turn, underscoring the value of physical interaction with digital systems. It also discusses recent advancements in living organisms as integral elements in design, aimed at reducing environmental impact and creating new user experiences. Through a systematic literature review and an in-depth analysis of case studies, the article proposes an extended definition of "livingness" across the three disciplines, advancing the understanding of the functions of living artefacts, how life-like capabilities can be integrated into them, and the implications for regenerative design. The findings invite a reimagined relationship between humans, materials and technology, fostering sustainable and interactive design practices.

Keywords: design, livingness, living materials, living artefacts, HCI, synthetic biology

1. Introduction

The fields of material science, design and human–computer interaction (HCI) are undergoing a significant shift toward recognising the vitality and agency of matter. This transformation is evident in the discourse around new materialism, which challenges the traditional view of materials as inert (Bennett 2010). New materialism emphasises the dynamic qualities of matter, suggesting that both organic and inorganic materials possess capacities for self-organisation, transformation and interaction. This shift has profound implications for fields beyond the humanities, influencing practical applications in design, technology and biology.

HCI has traditionally focused on the immaterial aspects of digital interaction, often perceiving systems as abstract representations of reality. However, the "material turn" in HCI has blurred the lines between digital and physical interactions, highlighting the role of tangible materials in user engagement. Research in this area explores how humans interact with digital information through their natural ability to perceive and manipulate physical objects (Ullmer & Ishii 2000), fostering novel sensory engagements with both digital and physical matter (Vallgårda & Redström 2007; Giaccardi & Karana 2015; Dragicevic, Jansen & Vande Moere 2021).

In recent years, design practices have increasingly integrated living organisms, such as algae, bacteria, fungi and plants, into the creative process. This

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Corresponding author
Venere Ferraro
venere.ferraro@polimi.it

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approach seeks to minimise environmental impact while exploring alternative material expressions (Camere & Karana 2018; Zhou *et al.* 2024). Researchers are also bridging biological and technological realms through bio-based materials and digital technologies (Bedau *et al.* 2010; Parisi, Holzbach & Rognoli 2020; Thundathil *et al.* 2023), enriching design with sustainable interaction methods. Such practices may fall under the umbrella of Bio-design, extensively conceptualised by William Myers in his book "Bio Design: Nature, Science, Creativity" (2012).

At the intersection of these developments lies the concept of "living artefacts" – objects with life-like properties that respond dynamically to their surroundings. These artefacts incorporate natural, engineered, or programmable materials, opening new possibilities for interactive and regenerative user experiences. This research aims to define, classify and explore the practical design and implementation of these living artefacts, focusing on "livingness" – the capacity of materials and objects to exhibit life-like behaviours.

The article has two main objectives: (i) to offer a comprehensive understanding of living artefacts as a design approach that aligns technology with nature, fostering meaningful interactions and (ii) to investigate practical applications by mapping their characteristics and potential. The study addresses key questions:

1. What defines livingness within living artefacts, and what implications does it have for design?
2. How can living artefacts be classified by their degree of livingness, purpose and function?

Through a systematic literature review and case study analysis, the research synthesises insights from new materialism, HCI, sustainability and bio-design and explores real-world examples across design, architecture and synthetic biology. The goal is to further establish a framework for designing artefacts that not only perform specific tasks but embody adaptive, life-like qualities. Such a framework should include key considerations about ethical stances when designing with and for livingness, which at the current stages is not yet widely considered as an emergent matter within the research community. Albeit outside the scope of this article, authors report ethical considerations when found in the literature; such considerations have been approached almost exclusively by papers from domains of synthetic biology and engineered living materials.

By positioning living artefacts within the broader new materialism discourse and material-centric HCI approaches, this article contributes to an emerging understanding of our interaction with materials. It shifts away from human-centred design and promotes a holistic perspective that values the agency of matter and encourages co-evolution between humans and the environment. In particular, the artefacts discussed in this study echo the biomimetic design method that seeks inspiration from biological realities and examines nature's designs for sustainability (Faludi, Yiu & Agogino 2020). While, from a philosophical perspective, matter is never inert but is always alive, engaging in a constant negotiation of agency and status with its surrounding ecology (Bennett 2010), this article focuses on material explorations and artefacts that mimic life-like abilities on a human scale, both spatially and temporally, rather than at a microscopic level.

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Livingness and living artefacts represent a forward-thinking approach to design that integrates human activity with ecological principles, fostering relationships that are both functional and sustainable. This method invites deeper engagement with the living world, challenging the conventional roles artefacts play and envisioning adaptive systems capable of co-evolving with nature.

2. Theoretical background

2.1. New perspectives on materialism

"New materialism" is an emerging theoretical framework in the humanities and social sciences that challenges traditional views of matter as passive and inert. Instead, it focuses on the materiality of bodies within social relations, accentuating the agency, vitality and self-organising abilities of matter (Ellenzweig & Zammito 2017).

This approach often intersects with feminist theory, particularly in the works of scholars like Donna Haraway and Karen Barad. Barad introduces a shift from "representationalism" – which assumes a separation between the one who represents and what is represented – towards "performativity." Representationalism, according to Barad, imposes a dualistic nature/culture divide and overlooks the inherent liveliness of matter. In contrast, her performative post-humanism sees reality as a web of entangled actors, each influencing one another through their paths and tendencies (Barad 2003).

Diana Coole and Samantha Frost also contribute to this conversation, offering a pluralistic view within "new materialisms." Coole (2013) summarises five core aspects of this approach: matter is not static but in a continuous process of materialisation; it is not passive but contains its own energies and transformative capacities; it is not fully predetermined by external factors, allowing for unexpected, non-linear developments; matter possesses agency; and – in the same line as Barad – the traditional nature/culture and human/non-human dichotomies of social constructivism are challenged and rejected.

By focusing on the agency and "livingness" of matter, both Barad and Coole advocate for a post-anthropocentric worldview, where humans and non-humans are interconnected within a constantly evolving system, as Donna Haraway suggests (Haraway 2010). This perspective also critiques the hierarchical classification of species, which places humans above animals and ultimately above inanimate matter.

Political theorist Jane Bennett expands on this by proposing a form of vitalism, attributing agency to non-organic materials like metals or plastics, and natural forces such as storms. Drawing from Spinoza, Latour and Merleau-Ponty, Bennett argues that these materials have their own "thing-power" – their own tendencies and trajectories, independent of human control. This idea of "vibrant matter" suggests that objects continue to act and influence the world, even when discarded (Bennett 2010).

By placing "livingness," agency and vibrancy at the core of this discussion, new materialism challenges traditional views of matter as lifeless and passive (Bennett 2010). This shift has far-reaching implications for ethics, politics and ecology, offering a fresh perspective on the material world and influencing how artistic and design practices engage with matter (Braidotti 2017; DeLanda 2019).

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2.2. A material turn between human-computer interaction and sustainability

New perspectives on materialism are reflected in what is known as the "material turn" within HCI. Previously, interactions with computing were seen as abstract and immaterial. However, computing is made possible through the careful arrangement of both physical and digital elements. In his book *The Materiality of Interaction*, Mikael Wiberg argues that the material turn has blurred the distinction between reality and representation by embedding computing into the physical and perceptual dimensions of our world. This shift marks a move from representation-centred design to material-centred design, where physical materials play a crucial role in interaction (Robles & Wiberg 2010; Wiberg 2018).

Wiberg's work introduces material-oriented approaches for interaction design, including tangible user interfaces (TUIs) and craft-based methods that emphasise the role of physical materials. This approach redefines interaction by focusing on how humans engage with materials, rather than purely abstract digital interfaces.

Several authors have highlighted the importance of materiality in designing physical objects that embody digital information (Kwon, Kim & Lee 2014). These designs foster first-person, lived and bodily experiences (Petreca *et al.* 2023), while also making use of the unique structures and qualities of computers (Vallgårda & Redström 2007). Anna Vallgårda and Johan Redström introduced the concept of "computational composites" to highlight the need for computational technology to be treated as a material in design. For them, computers should be paired with other materials, forming composites such as computational textiles and computational concrete.

Vallgårda *et al.* also introduced "material programming," a practice that allows designers to explore and manipulate the materials they are working with in real-time and in situ. This approach keeps designers engaged with the physical realm of materials throughout the design process (Vallgårda *et al.* 2016). Similarly, Parisi, Rognoli & Sonneveld (2017) introduced the idea of "material tinkering," which encourages designers to develop sensitivity to materials through hands-on, experiential learning.

Elisa Giaccardi and Elvin Karana (2015) compiled a significant body of material-oriented approaches in HCI. They proposed that materiality should be a central focus in design research, allowing for a deeper understanding of the possibilities and constraints of design. One foundational example is the project *Good Night Lamp* (2005) by interaction designer Alexandra Deschamps-Sonsino. The system consists of interconnected lamps, where lighting the central lamp automatically triggers smaller lamps to illuminate. The design conveys an intimate message from the person lighting the central lamp to their loved ones through the warm glow and soft, translucent materials (Deschamps-Sonsino 2015).

The *affective sleeve* by Papadopoulou (2024) exemplifies how materials can actively mediate emotional states by translating physiological signals into haptic feedback. Grounded in the concept of "Affective Matter," the project explores "Material Intelligence" (that is, the material's ability to sense and respond) as one possible foundation to support emotion regulation and wellbeing in HCI.

As materials take on a more prominent role in HCI and interaction design, researchers are also considering sustainable approaches. Eli Blevis (2007) proposed the "Sustainable Interaction Design" (SID) framework, which places sustainability

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at the core of interaction design. SID encourages minimising environmental impact throughout a product's lifecycle by promoting reuse, renewal, disassembly and responsible disposal.

Alongside the application of the sustainability paradigm within the design process, over the last decade the collaboration between design and biology has increased. The field, widely referred to as bio-design, configures as an emerging design practice, which integrates biological materials and processes often employing an array of techniques and technical implementations (Camere & Karana 2018; Kim *et al.*, 2023). A foundational, systematic body of work on bio-design has been published by Myers (2012). The book collects over 70 projects, which harness living materials and processes to solve specific problems, covering the fields of architecture, education, bioengineering, fine art and industrial design.

Within bio-design, a growing focus on bio-based materials for interaction design is emerging. These materials, derived from living or once-living organisms, offer the potential to decompose or biodegrade at the end of their lifecycle. For example, Pataranutaporn *et al.* (2020) introduced the concept of "Living Bits," which integrates microorganisms into computing systems. This builds on the earlier notion of "Tangible Bits," which bridges the digital and physical worlds (Ishii & Ullmer 1997) and expands it to create connections between computational and biological systems.

Bio-HCI, or biological human–computer interaction, is a growing research field that integrates biological materials into interactive interfaces (Pataranutaporn, Ingalls & Finn 2018). Several examples of bio-based material experimentation are found in the literature, including a breastplate made from SCOBY (Symbiotic Culture of Bacteria and Yeast) biofilm (Bell *et al.* 2023), a biodegradable biofoam for interaction design applications (Lazaro Vasquez *et al.* 2022) and a vinyl-like material made from marine algae, called "ALGANYL" (Bell *et al.* 2022).

Designers are now exploring bio-based materials using craft, digital fabrication and Do-It-Yourself (DIY) techniques, opening new avenues for material exploration (Ayala-Garcia & Rognoli 2017). The growing DIY movement is largely supported, as visible in catalogued designs, since low-cost prototyping and reduced fabrication effort facilitate experimentation and knowledge sharing. In the same way, digital fabrication – especially additive manufacturing (AM) – enables the direct production of physical artefacts from digital models, drastically reducing the effort, cost and environmental impacts to fabricate complex geometries (Camburn *et al.* 2017). Open-source software and learning resources, along with modular and adaptable electronic hardware, further empower end users to participate directly in design and manufacturing, fostering what can be described as a "democratisation of design" (DoD) (Goudswaard, Nassehi & Hicks 2023). Moreover, digital manufacturing technologies allow mass customisation (MC) and even mass personalisation (MP) (Ozdemir, Verlinden & Cascini 2022). These characteristics are foundational for the integration of living organisms in bio-based materials, especially considering the new opportunities that they give for both designers and other professionals, enabling collaborative exploration and innovation in material development. On one hand, engineers and all the "non-designers" can be involved in the idea generation and product development processes without having a formal design background (Goudswaard *et al.* 2023). On the other hand, technologies such as AM are already widely employed in the development of materials in the biological and biomedical fields (Kussmaul *et al.* 2019) as well as in composite and hybrid materials (Türk *et al.* 2019),

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thereby allowing designers to replicate and build upon what engineers and biologists have demonstrated to be possible. While these sustainable approaches to interaction design have shown promise in minimising environmental impact, most projects integrate living organisms only in the production phase. This is partly because prototyping has been shown to be crucial in exploring and understanding novelties in design. Physical prototypes, in particular, have been proved to boost creativity and resourcefulness, assist in evaluating concepts and facilitate understanding of form, feel and function, with purposes such as learning, communicating, integrating, or serving as milestones (Dordlofva & Törlind 2020; Petrakis, Wodehouse & Hird 2021). In this context, prototyping becomes a critical step not only for product development but also for integrating living organisms into bio-based materials, enabling experimentation, iteration and the translation of novel material properties into tangible, functional designs. However, there is less focus on sustaining these organisms during the usage phase, meaning the potential for interactions between humans and non-human agents remains underexplored. This gap reflects broader eco-design challenges as the need to reduce environmental impact through optimal resource use and to better understand usage patterns over time (Kim *et al.* 2020; Delaney *et al.* 2022) continue to constrain a holistic understanding of material agency. As a result, the behaviours and relationships these materials could foster are still an open area of inquiry.

3. Methodology

The evolving perspectives on materialism, HCI, highlight the increasing role of materiality in shaping sustainable interactions. These frameworks suggest a paradigm shift towards understanding matter as active, self-organising and capable of fostering new, symbiotic relationships between humans, technology and the environment. The concept of living artefacts emerges as a powerful tool to embody this shift.

To build on these theoretical insights, the authors considered as essential to investigate how living artefacts are defined, classified and implemented. To this end, the research involved a methodical exploration of the existing literature to analyse the current understanding of livingness in artefacts. In this section, the authors outline the methodology employed to conduct a comprehensive literature review, along with the research questions that guided this inquiry.

3.1. Systematic literature review

This study conducted a systematic review of the literature on the concept of "livingness" in design artefacts and materials. The review aimed to capture, evaluate and summarise existing research on the topic (Creswell & Creswell 2018). Given the emerging nature of the field, the bibliographic research focused on framing and conceptualising how "living artefacts" are understood and designed within scientific literature across various backgrounds and institutions.

3.1.1. Research questions and methodology

As recommended by Clarke (2009) in *The Handbook of Research Synthesis and Meta-Analysis*, the review process began by defining key research questions. These questions guided the study's objectives:

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1. How can artefacts be classified based on their level of livingness?
2. What are the characteristics of living artefacts?

To answer these questions, the systematic literature review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol (Liberati *et al.* 2009) This rigorous methodology ensured a transparent and accurate synthesis of the literature, while minimising bias and ensuring the integrity of the results.

3.1.2. Data collection

The review followed Liberati *et al.*'s four-phase flow diagram (2009) and was carried out from November 2023 to March 2024 (see Figure 1). Searches were performed in Scopus and Google Scholar to capture potential gaps in science-based databases and include applied research contributions. Specifically, Google Scholar was enquired to include studies closely related to Bio-design field.

Phase 1 – Identification.

The Scopus database search utilised terms like "living artefacts" and "living material." This search was limited to article titles and abstracts and filtered by subject areas (engineering, material science, multidisciplinary, computer science, arts and humanities, chemical engineering, neuroscience). This initial search returned 230 articles, with one duplicate excluded, leaving 229 articles.

Phase 2 – Screening.

In Google Scholar, a set of keywords ("living artefacts," "bio-design," "livingness," "more-than-human") was used to identify additional documents. Of the 38 records found, 30 progressed to the next stage. Each article underwent title, abstract and keywords screening by two co-authors to determine relevance to the research questions. Articles lacking direct relevance were subjected to full-text reading for further assessment.

Phase 3 – Eligibility.

Next, the articles were reviewed in detail against inclusion/exclusion criteria. Reasons for exclusion included limited access, alternative interpretations of living materials, irrelevance to the study's objectives, highly technical language and emphasis on workshop or activity calls. This phase excluded 180 articles from Scopus and 21 from Google Scholar.

Phase 4 – Inclusion.

Following this review, 58 full-text records were included. A further 3 articles, identified through the "snowballing" technique, were added to address potential gaps. These papers were particularly relevant to the keyword "agential materials." The final total included 61 records.

An Excel matrix was created to organise and categorise the selected articles for detailed analysis, as described in the next section.

3.1.3. Data analysis

The authors used an Excel spreadsheet to annotate the records identified in the literature review. The 61 eligible contributions (including conference papers and full articles) were then subjected to further analysis.

For each record, the authors provided a concise summary and a set of relevant keywords that clarified the core contribution of each paper to the research questions. Both co-authors reviewed the keywords for consistency, standardising

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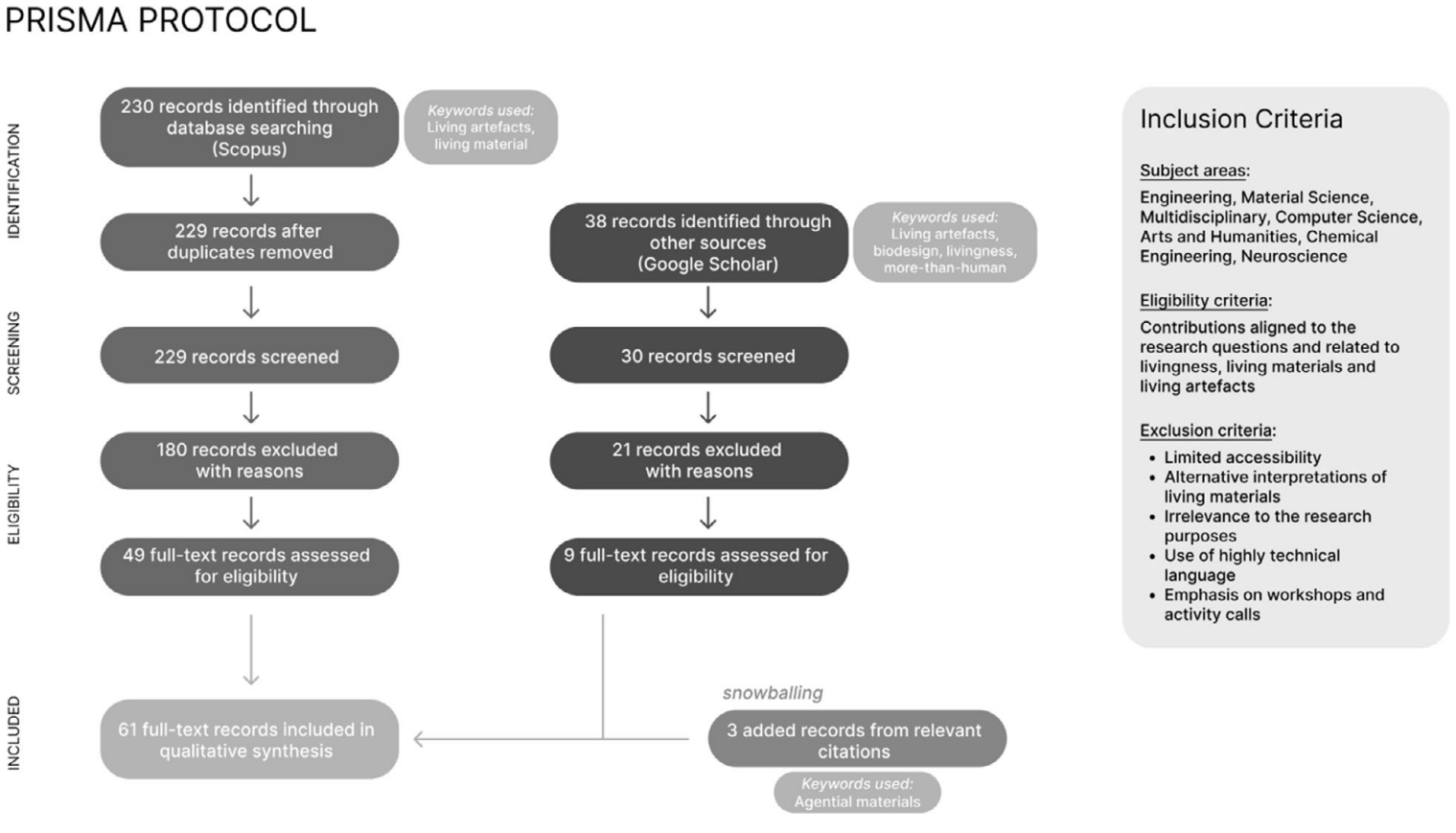


Figure 1. PRISMA four-phase flow diagram by Liberati *et al.* (2009) illustrating the process of the systematic review.

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them based on specific criteria. For instance, variations like "engineered living materials," "Engineered Living Materials," and "ELMs" were unified under the term "Engineered living materials." Similarly, synonymous concepts like "Biological HCI" and "Bio-HCI" were harmonised, with the latter selected as the preferred term.

During the activity, the authors also annotated definitions provided by the papers, aiming to compare various understandings of "livingness," "living artefacts," and "living materials." This helped clarify whether a comprehensive definition of these concepts existed in the literature. When applicable, the approaches and methods used to explore "livingness" were also noted, and like the keywords, they were standardised and clustered where necessary – for example, "Material tinkering" was consolidated under "Tinkering."

Throughout the analysis, the authors observed significant variation in how "livingness" was defined and approached across different disciplines. To address this, three recurring macro-areas were defined – design, HCI and synthetic biology – and each record was categorised under one of these areas. This classification helped reveal correlations between disciplines, definitions and approaches.

To further support the analysis, the data was visualised using Gephi software (see Figure 2). The network visualisation allowed the authors to map the following: (i) the presence of keywords in specific disciplines; (ii) the frequency of keyword occurrences and (iii) the areas of interdisciplinarity and co-occurrence. This visualisation acted as an additional tool to extract key findings, which are discussed in the *Results* section.

4. Results

4.1. Navigating the concepts of livingness, living materials and living artefacts

As discussed in Section 3.1.3 (*Data Analysis*), the authors identify design, HCI and synthetic biology as three disciplines that offer distinct definitions and understandings of "livingness," "living artefacts" and "living materials." Despite their differences, these disciplines overlap to some extent, enabling the authors to propose a more comprehensive definition of these concepts that can significantly enrich this emerging research area.

Delving into the design discipline, livingness refers to the quality of being alive, encompassing the biological characteristics that define living organisms – such as growth, metabolism, response to stimuli, reproduction and adaptation. This concept extends beyond mere biological definitions. It also considers the interactions between living entities and their environments. Our understanding of livingness has evolved to incorporate ecological perspectives, suggesting that living systems exist in dynamic interrelations, forming complex adaptive ecosystems (Karana, Barati & Giaccardi 2020).

From a design standpoint, livingness highlights the experiential aspects of engaging with living materials. Designers are encouraged to create artefacts that not only utilise living organisms but also foster relationships between humans and these organisms. This approach can take many forms, ranging from biophilic designs that integrate nature into everyday life (van den Broek, de Rooji & van

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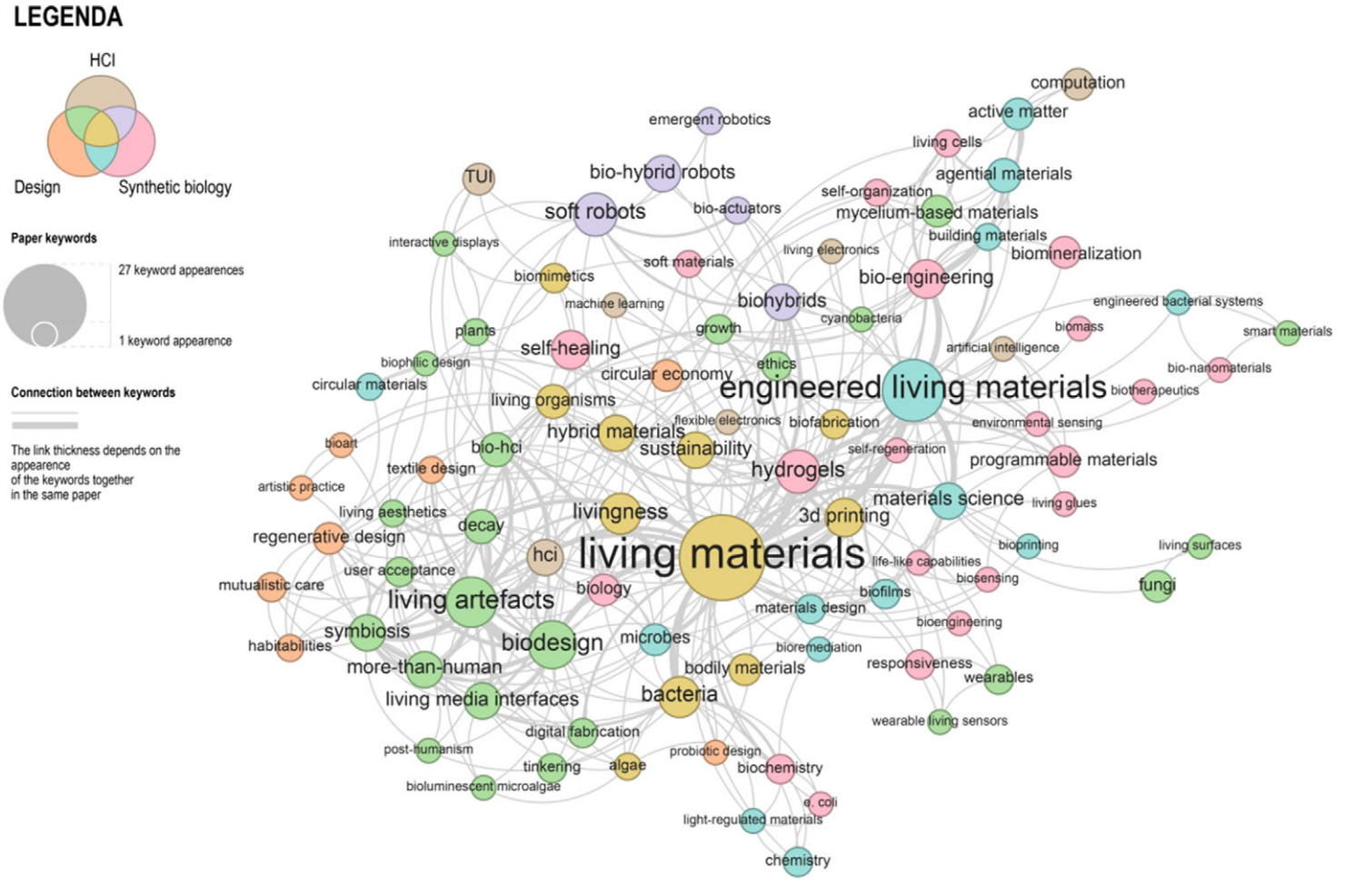


Figure 2. Keywords network of the systematic literature review.

Dartel 2022) to artefacts that dynamically interact with their surroundings, providing both aesthetic and functional experiences.

Living artefacts are specifically designed to sustain the vitality of the living organisms they contain, allowing these organisms to thrive as part of the artefact's functionality. This concept emphasises the integration of biological processes into design outcomes. Living artefacts can serve various roles, including biosensors, energy generators and nutrient recyclers. For instance, furniture incorporating microalgae can enhance energy sustainability by utilising light, heat and carbon dioxide from their environment (Karana *et al.* 2023).

The framework for living artefacts is often based on principles that prioritise ecological interdependence, mutualism and the cultivation of more-than-human sensibilities. This encourages designers to create artefacts that not only address human needs but also recognise the agency and requirements of non-human life forms (Groutars, Kim & Karana 2024). For instance, Karana *et al.* (2020) refer to living artefacts as objects which will decay and eventually die. Albeit the potential of sustaining vitality, studies on the sustainability of integrating bio-organisms into designed artefacts are currently scarce. However, other research fields such as material science, discussed later in this paper, may offer more reliable approaches to embedding livingness into everyday products, moving beyond the current fragility and uncertainty.

Livingness and living artefacts challenge traditional design paradigms by advocating for non-hierarchical relationships between humans and non-humans. The presence of livingness calls for the development of collaborative and co-design processes, particularly relying on strong interactions among participants, transitioning from individual creation to shared co-creation (Ehkirch & Matsumae 2024). This perspective encourages a rethinking of our interactions with environments, promoting sustainability through regenerative practices. Furthermore, the integration of living artefacts into daily life is not merely a technological endeavour but a cultural one, aiming to reshape societal views on the role of living organisms in our environments. Consequently, a significant rebalancing of design thinking is required: one that can support the design of a sustainable educational ecosystem through interdisciplinary overlaps, openness and transparency and that is equipped to address future challenges (Berglund 2024). Such changes can lead to transformative shifts in how we perceive and engage with the natural world (Karana *et al.* 2020, 2023).

According to Dew & Rosner (2018), livingness encompasses the inherent qualities of materials that actively change over time, demonstrating characteristics such as growth, decay and regeneration. From this perspective, living materials should not be viewed as passive resources; they are dynamic design resources that inherently change and evolve. For example, wood possesses a life history characterised by growth patterns, scars from past experiences and changes due to environmental factors.

This perspective invites designers to acknowledge and engage with the temporal and spatial properties of materials, treating them as active collaborators in the design process rather than mere objects to be manipulated. Moreover, designers must adopt a reflexive approach throughout the entire process, as it enables them to respond dynamically to the evolving and unpredictable nature of living artefacts while also enhancing ethical awareness, methodological flexibility and the relevance of research outcomes (Reich 2017).

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In the context of HCI, livingness is increasingly recognised as a material quality that enhances user engagement, empathy and understanding of non-human agents (e.g., microbes, plants). It involves making the vitality of these living components apparent to users, thereby enriching experiences and fostering a sense of care and interaction between humans and living systems (Kim *et al.* 2023). While the user experience of traditional products is often assessed using established indicators such as "user comfort" and "user delight" (Liao, Tanner & MacDonald 2019), leveraging affective, cognitive and ergonomic dimensions (Berni *et al.* 2023), new indicators should be proposed and tested for living artefacts.

This viewpoint is consistent with the definition by Sankaran *et al.* (2018) of living materials as a class of materials that integrate the properties of living organisms, exhibiting productive, adaptive and regenerative capabilities. Unlike traditional static materials, these living materials can respond to environmental stimuli and interact dynamically with their surroundings; they can be regulated to alter their properties or functions in response to external stimuli, allowing for more responsive interactions. Furthermore, they can be engineered to integrate with human cells or other biological systems, facilitating targeted delivery of therapeutic agents or enhancing tissue engineering.

According to De Rossi & Ahluwalia (2000), living artefacts are designed objects or systems that incorporate living biological elements, such as microorganisms, plants or other life forms, enabling them to exhibit qualities associated with life. These artefacts can adapt, respond to stimuli and dynamically interact with their environment, effectively bridging the gap between biological and artificial systems. They combine synthetic materials with biological components to create hybrid systems that leverage the advantages of both worlds, including self-regeneration and adaptability.

The discussion of living artefacts and living materials becomes even richer when considering the field of synthetic biology. According to Peng *et al.* (2023), living materials represent a new frontier in functional material design, integrating synthetic biology tools to imbue materials with programmable, dynamic and life-like characteristics. This innovative paradigm merges synthetic biology and materials science to create engineered living materials (ELMs), which exhibit multifunctionality, adaptability, resilience and potential evolvability. ELMs consist of living cells, such as bacteria or fungi, embedded within an organic or inorganic matrix. These materials are engineered to perform complex behaviours such as sensing, responding to stimuli and producing biologically functional outputs (Wang *et al.* 2023).

By merging living cells with different material substrates, ELMs exhibit life-like characteristics such as self-repair, responsiveness and growth. This fusion facilitates the development of functional, adaptive and potentially intelligent materials by combining living cells with various matrices (Nguyen *et al.* 2018; Wang, Jiang & Sun 2020; Wang *et al.* 2023).

These living materials offer applications in biofabrication, biosensing, wearable technologies and sustainable material production by linking material properties to biological activities.

In their work, Appiah *et al.* (2019) focus on the advancements and potential applications of biohybrid soft robotics, which combine living cells with synthetic materials to create adaptive and functional structures. However, the integration of living materials into robotics inevitably raises complex ethical questions,

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encompassing not only the design of appropriate interactions where privacy and regulatory compliance must be carefully addressed (Pereira Pessoa 2020) but also regarding the sourcing, manipulation and the potential impacts on both the organisms involved and the environment. These concerns include both the long-term effects of using living cells in biohybrids, as well as broader societal implications of manipulating biological matter to serve certain purposes. A recent work by Ebbesen *et al.* (2024) highlights potential risks, including misuse or dual use with public health and security implications (e.g., bioterrorism and weapons development). Additional safety issues include potential biohazards of the building blocks employed for the creation of ELMs, leading to severe and disruptive scenarios concerning researchers and people's health and wellbeing. Addressing these ethical issues is crucial as the field progresses.

In a few scientific papers pertaining to synthetic biology, specifically bioengineering, the term "Agential" is used as an integrated feature of "livingness" when describing materials. In a proposal for *Research Directions*, Dade-Robertson, Levin & Davies (2023) invite contributions that demonstrate and explore the use of "Agential Materials" across applications that extend beyond the current ones of bioengineering. In this context, agency replaces familiar concepts of command and control with that of collaboration between scientists and the material itself. Ultimately, scholars in this area foresee that agential materials will nurture emerging intersections between biological and computational sciences (Davies & Levin 2023). This notion of material agency resonates with the philosophical approaches mentioned in the first part of this article, such as Jane Bennett's "vibrant matter" (2010).

In summary, it can be concluded that (i) design utilises living materials in the creation of everyday objects that remain alive during user interactions; (ii) HCI integrates living organisms into digital products or systems to perform specific functions, often replacing electronic components and (iii) synthetic biology focuses on living systems, applying engineering principles to develop new biological devices and systems or to redesign existing natural systems.

4.2. Living artefacts and regenerative futures

The concept of livingness and living artefacts emerging from interdisciplinary explorations at the intersection of biology, design and technology signals a shift towards more sustainable and symbiotic relationships between humans and their environments. This exploration invites a transformative rethinking of design, advocating for the integration of biological principles into daily life. This emerging field addresses practical challenges while reshaping cultural attitudes towards nature and living systems, fostering a deeper appreciation for the complexities of life and ecological interdependence. This integration of science and design, especially if aligned with a business-oriented direction, is proven to give life to a "united innovation process" capable of fostering new knowledge, enabling innovative design opportunities and driving pioneering inventions (Luo 2015).

The concepts of livingness and living artefacts promote an integrated, conscious approach to design that aligns with the principles of life and ecology, resulting in innovative, responsive and sustainable solutions. By embedding living systems into design, these concepts provide a powerful framework for

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reimagining human interaction with the world, encouraging more sustainable and reciprocal relationships with the environment and contributing to regenerative ecosystems.

Living artefacts represent an innovative approach that harmonises technology with the natural world, fostering interactions that are both functional and empathetic towards life. This paradigm shift invites designers and researchers to explore new approaches that prioritise sustainability and biological integrity in the creation of future artefacts.

Integrating living organisms into design paves the way for a regenerative future. Regeneration, which embodies "rebirth" or "renewal," has become an essential principle in eco-design, promoting the co-evolution of human and natural systems. Regenerative design supports systems capable of self-renewal and replenishment, seeking to enhance the health of ecosystems rather than merely minimising harm. This approach is holistic, positioning humans and nature as interconnected entities rather than separate, as often seen in conventional sustainability practices. It emphasises an adaptive, dynamic system that relies on interdisciplinary methods to uphold the significance of nature.

As proposed by Karana *et al.* (2023), living artefacts could facilitate the development of "regenerative ecologies," as self-organising systems where humans and nature co-evolve and coexist, promoting biodiversity and mutualism while integrating living organisms, materials and forms of agency to foster creativity and adaptation.

Incorporating living organisms into design and everyday artefacts holds great potential for promoting regeneration at various ecological scales, fostering a more harmonious and balanced relationship between humans and non-human species. This approach moves beyond conventional design and sustainability, advocating for a future where human-made systems work synergistically with natural processes, enriching both human life and the broader ecosystem.

5. Discussion

5.1. Defining "livingness"

Considering the fragmented panorama of living artefacts sometimes defined as living materials or engineering living materials, authors decided to conceptualise the word "livingness" instead, through a threefold schema with three layers, unfolding how it can be enhanced and triggered in artefacts. These three layers are natural matter, engineered matter and programmable matter. Each layer presents unique approaches and techniques, from mimicking natural systems to engineering living cells and programming materials with life-like characteristics. They can be attributed to the three disciplinary fields mentioned above. Synergically, these layers provide a model for the development of artefacts that not only perform specific functions but also embody the dynamic and adaptive qualities of living organisms, perhaps engaging in what Barad defines as "performativity" in the material world (Barad 2003). Manipulating living matter raises significant ethical considerations, particularly at the microscopic, genetic scale. Although this aspect is not deeply explored in the paper, it is recognised as a crucial gap in the existing literature on livingness and living artefacts, analysed across design, HCI and synthetic biology.

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Figure 3. *Future Flora* by Giulia Tomasello, a speculative harvesting kit designed for people with vaginas to treat and prevent vaginal infections.

Natural matter

Natural matter refers to materials that are derived directly from living organisms or natural systems. This layer focuses on integrating the actual living organisms or materials into artefacts, perhaps with the aims of reducing the environmental footprint, creating novel aesthetic narratives or improving the functional properties of a material/artefact (Barati *et al.* 2021; Zhou *et al.* 2022; Kim *et al.* 2023). The living organism is integrated into the artefact with little or no manipulation, thus exploiting its properties until it dies or decays (i.e., the luminescence property found in certain types of algae).

Living artefacts which leverage natural matter could encourage a relationship of mutual benefit between themselves and users, like symbiotic relationships found in nature (see Figure 3). For example, a living artefact may require care and, in return, provide aesthetic or functional benefits, promoting a more engaged and interactive experience (Keune 2021). Designing living artefacts enabled by natural matter poses opportunities and challenges. To begin with, it could leverage sustainable behaviours from the user to the company, reimagining ways through which artefacts are produced, looking at DIY processes and delocalised production.

A challenge of living artefacts lies in the user acceptance of a novel and unprecedented aesthetic, which might not be smooth or uniform but rather evolve over time and decay. In this regard, Salvia *et al.* (2010) talk about "imperfection and material traces" to give new value to what is addressed as imperfect and to elevate material traces left by time to reinforce an emotional link between users and artefacts.

Engineered matter

Engineered matter focuses on the construction of materials at the cellular or molecular level, often using techniques from the field of synthetic biology. The goal is to design new materials that exhibit specific, desired functionalities that do not exist in nature, or to enhance natural materials' properties for specific applications. These could range from bacteria engineered to break down pollutants to cells designed to produce renewable energy (Li *et al.* 2023) (see Figure 4). In contrast with natural matter, engineered matter presupposes a deliberate manipulation by humans.

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Figure 4. *Phyto Printing* by Luis Undritz, A light projection to control the growth of phytoplankton to create high-resolution prints.

A significant innovation in engineered matter is the development of the so-called engineered living materials (ELMs), which integrate living cells into non-living structural frameworks. These materials can adapt, repair themselves and respond to environmental changes, combining the robustness of traditional materials with the adaptability of living organisms. Wang *et al.* (2023) discuss the use of ELMs in creating responsive materials for medical implants that can adapt to the body's environment, enhancing compatibility and reducing the need for replacement surgeries. So far, the application fields of ELMs have been quite limited to biology and medicine, nonetheless, several researchers are exploring the potentialities of ELMs in architecture (Elsacker, Zhang & Dade-Robertson 2023) and design (Kafai & Walker 2020) as well.

Programmable matter

Programmable matter represents a new frontier in materials science, where materials are designed to change their properties in response to external stimuli. This layer bridges the gap between living and non-living systems, by embedding life-like characteristics into materials that are not traditionally considered living.

This approach leverages new classes of materials, such as shape-memory alloys, smart polymers and responsive gels, that can be programmed to exhibit specific behaviours (see the example in Figure 5). These materials have applications in various fields, including soft robotics, where they can enable machines to move and adapt in life-like ways. In regard to "livingness," programmable materials grant smartness features to inert materials; in other words, they become able to respond to potential risks, adapt to changes and perform certain actions when certain external conditions arise (Ozkan-Aydin, Goldman & Bhamla 2021). For instance, Graham *et al.* (2020) discuss the creation of hydrogels that change properties in response to environmental stimuli, which could be used in smart textiles or responsive building materials. This research opens possibilities for dynamic materials that interact with their surroundings in real time.

In this article, the authors argue that natural, engineered and programmable matter are not to be intended as separate categories where one excludes the other. Instead, they can be synergically approached as lenses to intend "livingness," or as methods to be used in different phases when designing living artefacts. Clearly, the array of expertise differs from one to another. Engineered and programmable matter might need several competencies and attitudes, which lie outside of the

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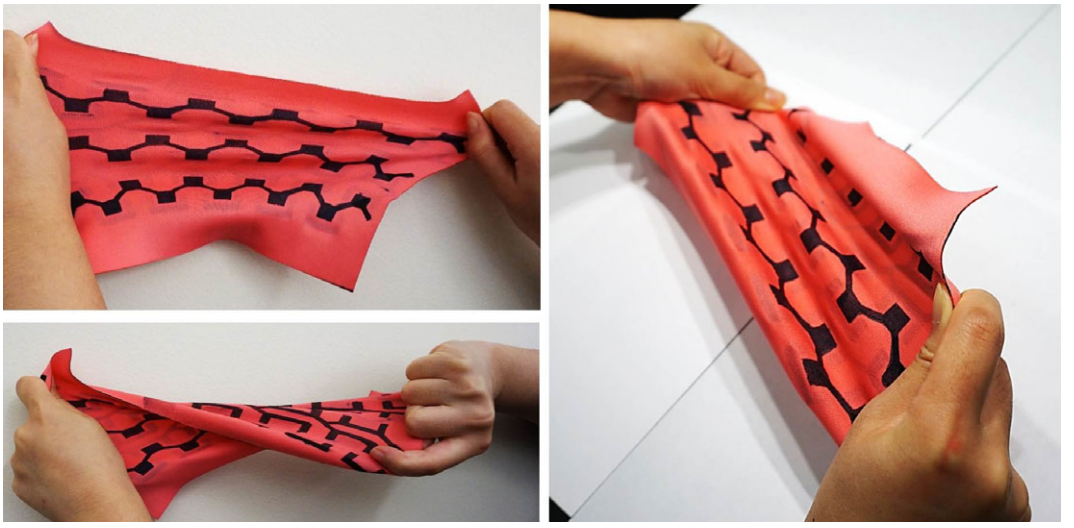


Figure 5. Textile-based flexible and stretchable biobatteries by Sumiao Pang, Yang Gao and Seokheun Cho.

design field: for this reason, interdisciplinary collaboration would be an indispensable lever to craft living artefacts.

In this regard, the authors propose an extended definition of "livingness," incorporating the three layers previously discussed: natural, engineered and programmable matter. The goal of this definition is to systematise various interpretations of "livingness" from the fields of design, HCI and synthetic biology. By uniting these perspectives, the definition aims to offer a comprehensive framework that expands the understanding of "livingness" across multiple disciplines.

"Livingness is enabled by Natural, Engineered, or Programmable Matter. It is the property to encode life-like abilities within artefacts, to enhance novel user interactions and foster regenerative futures."

Breaking down the definition in detail:

- **"Livingness is enabled by natural, engineered or programmable Matter":** This phrase identifies the materials through which "livingness" is achieved. The three layers – natural matter, engineered matter and programmable matter – represent different approaches and technologies that allow designers to imbue artefacts with life-like qualities. Each layer presents unique methods and capabilities, from using living organisms in design to programming materials to respond to external stimuli.
- **"It is the property to encode life-like abilities within artefacts":** Here, "livingness" is defined as a property, meaning an inherent characteristic or quality that artefacts can possess. It refers to the capacity to embed life-like qualities – such as growth, adaptation and response – into non-living or previously inert objects. This concept challenges traditional notions of material passivity and invites a rethinking of how artefacts can behave and interact with their environment.
- **"to enhance novel user interactions and foster regenerative futures":** Artefacts with life-like abilities enable new forms of user interaction, pushing beyond traditional user experiences. By encouraging unprecedented and symbiotic

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engagements between users and objects, these artefacts contribute to a future that emphasises sustainability, regeneration and ecological health. They are not just functional but interactive, influencing user behaviour towards more mindful and regenerative futures.

In the authors' opinion, the proposed definition of "livingness" not only systematises the diverse interpretations of this concept across disciplines but also serves as a foundation for future research and practice. By acknowledging the persistent risk of fragmentation across different design domains (Papalambros 2015) and unifying perspectives from design, HCI and synthetic biology and interpretation given by different scholars cited above, this definition provides a holistic framework that can be applied across a range of projects and sectors. It opens new possibilities for interdisciplinary collaboration, guiding both academic research and practical applications. In this regard, following the perspective of Kelly & Gero (2021), the authors position design thinking in relation to computational thinking, particularly in the context of living artefacts, highlighting their complementary roles in addressing complex and emergent challenges.

Furthermore, this definition contributes to the growing discourse around regenerative design by framing "livingness" as a catalyst for sustainable futures. Artefacts that exhibit life-like properties can foster deeper, more interactive relationships between humans and the material world, promoting an ecological awareness that aligns with the principles of regeneration and sustainability. As this research area evolves, the definition of "livingness" will play a key role in shaping new methodologies, tools and processes for creating artefacts that are not only functional but also alive, dynamic and ecologically integrated. The focus on user interactions might open compelling research trajectories on developing methods to enquire users' feedback while designing with and for livingness.

5.2. Case studies mapping

To validate the definition of "livingness" and answer the second research question posed in the introduction session – namely how living artefacts can be classified by their degree of livingness, purpose and function – the authors examined 44 case studies of living artefacts. These cases were drawn from various sources such as design platforms, academic records, research labs and exhibitions. In this regard, the authors acknowledge that the collection of case studies may lack a systematic approach, which could introduce some bias. Adopting a more narrative and exploratory approach allowed the authors to intentionally minimise bias and ensure a balanced inclusion of cases from several areas of design (product, fashion, interior), as well as HCI and synthetic biology. Nonetheless, the case studies analysis was systematic through the methodology of annotated portfolios (Bowers 2012).

The case studies played a crucial role in shaping and affirming the proposed definition by illustrating how life-like qualities can be embedded in artefacts through natural, engineered or programmable matter.

Several projects from the design field support the integration of natural materials into living artefacts. For example, Teresa van Dongen's *Spark of Life* (2016) lamp uses electrochemically active bacteria to generate light and electricity. The project exemplifies "livingness" by utilising natural matter in a functional and

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interactive artefact, blurring the line between organic and technological. Another example, *Deep Learning Insole* (2018), developed by Puma and the MIT Design Lab, which integrates microbial cultures to monitor biochemical signals, showcasing how living organisms can be embedded in everyday objects to enhance user interactions. Maca Barrera's *Melwear* (2024) uses microbes to produce natural sunscreen, leveraging biological properties to create a wearable living artefact.

In the intersection of interaction design and materiality, projects like Giulia Tomasello's *Future Flora* (2017-current) and Lucrezia Alessandroni's *The Soothing Cup* (2022) use livingness to enhance the user experience in relation to women's health. Both projects combine bio-based materials and digital interfaces to create artefacts that are responsive and adaptive, reaffirming how natural and engineered matter can lead to more intimate, personalised forms of interaction.

In the realm of synthetic biology and bioengineering, projects like *E. Chromi* (2009), a collaboration between designers and scientists at Cambridge University, demonstrate the potential of engineered matter. This project uses engineered bacteria ingested via yoghurt to detect diseases in the human gut, highlighting how bio-engineered materials can create living artefacts that go beyond traditional design boundaries. Similarly, the *Zero_Mile System* (2018–current), a collaboration between Politecnico di Milano and the Biology Department of Tor Vergata in Rome, integrates an engineered biological filter for reusing wastewater to grow plants, illustrating the potential of engineered living materials for ecological applications.

However, the case studies revealed that fewer examples exist within the realm of programmable matter. This observation aligns with the literature, which indicates that programmability in materials is still an area with untapped potential. One noteworthy case is the *Nano Cure Tech – Nylon Fabric* (2018), a self-healing nylon material capable of repairing itself with heat and pressure. Although examples of programmable matter remain limited, the potential for this layer to create dynamic, responsive artefacts is clear and warrants further exploration.

The case studies have been invaluable for several reasons. First, they have validated the proposed definition of "livingness" by providing concrete examples of how life-like abilities can be integrated into artefacts (see Table 1).

These examples span across various disciplines – design, synthetic biology and HCI – demonstrating the versatility and applicability of "livingness" in different fields. The projects illustrate how materials, whether natural, engineered or programmable, can be designed to engage users in new, interactive ways that promote sustainability and ecological awareness. Case studies from more traditional material design research were excluded, as they do not align with the definitions of living artefacts identified in the literature or with the extended definition proposed in this article. Including such material explorations would have required a significantly broader scope, ultimately diverting from the research question that guided this study.

Additionally, the case studies highlight the diversity of approaches, tools and methods required to design living artefacts. Each project reveals different processes for integrating life-like properties into artefacts, whether using microbial cultures, bio-based materials or programmable technologies. These insights will be critical in further refining the methodologies and frameworks for designing living artefacts, as well as in identifying the potential sectors where these artefacts can be most impactful.

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Table 1. Eight exemplary case studies selected from a collection of 44, analysed for their level of "livingness," purpose and function

no.	Image	Description	Layer of livingness	How it acts/ interacts	How it is developed	Source
1		*Ambio* by **Teresa van Dongen** is a lamp that harnesses the natural bioluminescence of microorganisms in a seawater-like medium, to create a soft light inspired by the glowing waves of the ocean.	Natural matter	Emitting Light	Bioluminescent Algae and Bacteria's Culturing	https://www.teresavandongen.com/Ambio
2		*Grow Your Own Couture* by **Piero D'Angelo** is a speculative fashion collection created through a series of DIY experiments to cultivate lichens, organisms capable of absorbing air pollutants.	Natural matter	Air Purification	Growing Design Process, Biofabrication, DIY Methods	https://www.pierodangelodesign.com/collections/grow-your-own-couture-the-collection
3		*Melwear* by **Maca Barrera** draws on the power of microbes to produce a naturally derived sunscreen that protects the body from harmful UV rays. It gradually darkens as it is exposed to the sun.	In between natural and engineered matter	UV Protection, Colour Changing (Feedback)	Bacteria's Culturing, Speculation	https://ualshowcase.arts.ac.uk/project/477855/cover

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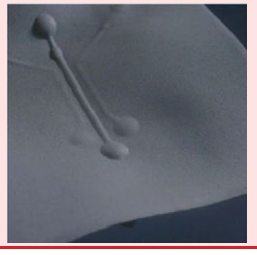
Table 1. Continued

no.	Image	Description	Layer of livingness	How it acts/ interacts	How it is developed	Source
4		*The Soothing Cup* by **Lucrezia Alessandroni** is a menstrual cup made from an algae-based hydrogel mixed with lactobacillus, becoming a membrane capable of interacting with the vaginal environment.	In between natural and engineered matter	Balancing Vagina Microbioma	3D Printing, Casting processes, Bacteria's Culturing	https://www.futurematerialsbank.com/material/sodium-alginate/
5		*Adaptive Packaging* by **PUMA + MIT Design Lab** contains two types of micro-organisms: yeast that produces CO_2 to inflate the bags, and bacteria that deflate them over time by breaking down the material.	Engineered matter	Inflation through air sacks, Shape Adaptation	Biofabrication, Bacteria's and Yeast's Culturing	https://www.orkantelhan.com/bio-design#/adaptive-packaging/
6		*Skin II* by **Rosie Broadhead** is a garment with encapsulated probiotic bacteria that activate when in contact with skin moisture, reducing body odour, stimulating cell renewal and improving the skin's immune system.	Engineered matter	Reducing Odour, Cell Renewal, Improving Immune System	Bacteria's Culturing, Biofabrication, Textile techniques	https://rosiebroadhead.com/

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Table 1. Continued

no.	Image	Description	Layer of livingness	How it acts/ interacts	How it is developed	Source
7		*E. chromi* by **Alexandra Daisy Ginsberg** is a detection system that employs engineered bacteria, ingested in yoghurt as chemical markers of disease, as easy-to-read warnings by staining the poo.	In between engineered and programmable matter	Colour Changing (Feedback)	Bioengineering Processes, Synthetic Biology Processes	https://www.daisyginsberg.com/work/echromi-living-colour-from-bacteria
8		*SELK* by **MotorSkins** is a multilayered textile structure that exemplifies the programmability of textiles, endowing it with the ability to sense, react and adapt to its surroundings	Programmable matter	Shape Adaptation, Physical Reaction	Soft Robotics, Fluid Logic, Programming, Bio-Inspired Design, Tissue Mimicking	https://designwanted.com/selk-technology-motorskins-interface-design/

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On a methodological note, the 44 case studies were organised into cards (see Supplementary Appendix 1), each containing a project description, details of development, layer of livingness and information on how the artefact interacts with users. Specifically, the details of development have been mapped in a progression line, from exploratory, experimental, to validated prototype.

By systematically analysing the case studies, this research has confirmed that the proposed definition of "livingness" offers a solid foundation for both academic and practical work in designing living artefacts. The diverse examples presented illustrate the potential of life-like abilities to foster novel user interactions and regenerative futures, particularly using natural, engineered and programmable matter.

6. Conclusions and further developments

This article aimed to provide a comprehensive understanding of living artefacts and investigate practical applications by mapping their characteristics and potential. To achieve this, it explored the evolving concept of "livingness," examining how natural, engineered and programmable materials can be harnessed to create artefacts imbued with life-like qualities. This research highlighted a new approach to designing living artefacts, emphasising the significance of materiality within design, synthetic biology and HCI. This shift moves away from viewing materials as passive elements, recognising instead their agency, adaptability and potential to foster novel user interactions that align with sustainable and regenerative practices.

The article addressed two main research questions: *What defines livingness within living artefacts, and what implications does it have for design?* And *How can living artefacts be classified by their degree of livingness, purpose and function?* To answer these, the authors proposed a three-layer framework encompassing natural, engineered and programmable matter for understanding and embedding "livingness" in artefacts, leveraging the unique properties of each type of matter individually or in combination. This novel framework enables artefacts to exhibit life-like qualities, incorporating perspectives of material agency, adaptability and interaction with humans and the environment. The framework with its main findings is summarised in the Table 2 below.

The study mapped 44 real-world case studies that demonstrated varying degrees of livingness and practical applications. These examples underscored how different types of matter contribute to specific functionalities, from bio-based materials integrated into everyday objects to engineered systems capable of self-regeneration and programmable responsiveness. This classification validated the proposed definition of "livingness" and showcased its versatility across different fields. However, in most cases, it remained insufficiently developed to be scaled up towards real-world applications, reflecting common challenges in the upscaling of emerging technologies (Riondet *et al.* 2024).

For design practitioners, this research introduced new possibilities for integrating living organisms such as algae, bacteria, fungi, programmable matter and digital technologies into novel artefacts. These approaches could not only minimise environmental impact but also open new expressions of materiality. In HCI, the material turn prompts a reconsideration of physical and digital interactions, centring material engagement to enrich user experiences. In materials science,

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Table 2. Framework matrix with main findings

"Livingness is enabled by Natural, Engineered, or Programmable Matter. It is the property to encode life-like abilities within artefacts, to enhance novel user interactions and foster regenerative futures."

Livingness layer	What it refers to	Core Discipline	Complementary Disciplines	Design implications
Natural matter	Materials derived directly from living organisms or natural systems with little or no manipulation.	Design	HCI	Enhancing the functional performance of an artefact or a material (e.g., using mycelium for sound absorbing wall panels). Reducing environmental footprint by replacing unsustainable resources and materials. Creating novel aesthetics inspired by biophilia. Unlocking user interactions based on mutual care and symbiosis.
Engineered matter	Materials constructed/ manipulated at the cellular or molecular level using techniques from the field of synthetic biology.	Synthetic Biology	HCI	Enhancing natural materials' inherent properties (e.g., integrating a protein to increase mechanical properties). Creating new materials with specific desired functionalities that do not exist in nature or are difficult to isolate (e.g., constructing a microbial consortium that filters wastewater). Requiring collaboration between designers and biologists. Developing interdisciplinary monitoring methods and tools to understand the materials' behaviour over time.
Programmable matter	Materials programmed to change their properties/ behaviours in response to external stimuli, resembling life-like characteristics.	HCI	Synthetic Biology	Reimagining rigid, static interfaces towards fluid, adaptive and life-like movements (e.g., soft robots). Granting smartness features into inert materials (e.g., self-repairing textiles).

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Table 2. Continued

"Livingness is enabled by Natural, Engineered, or Programmable Matter. It is the property to encode life-like abilities within artefacts, to enhance novel user interactions and foster regenerative futures."

Livingness layer	What it refers to	Core Discipline	Complementary Disciplines	Design implications
				Approaching materials as "data interfaces" (e.g., materials that react to temperature by changing colour).

recognising materials as active, adaptive participants within systems pushes the boundaries of sustainable technological innovation.

The research effectively bridges theoretical insights from design, HCI and synthetic biology to create a cohesive framework for crafting artefacts with regenerative and adaptive qualities. Integrating "livingness" into artefacts signals a forward-thinking approach to design, aligning with ecological concerns and redefining human and non-human interactions.

Nonetheless, this review presents limitations. First, the authors' backgrounds in design and HCI may have biased the framing of "livingness" towards a design-centric lens, potentially overlooking perspectives from other disciplines. Second, the focus on artefacts that exhibit living qualities during use excluded relevant cases, such as technical materials or architectural applications involving once-living but now inert matter. Third, the framing may have omitted artefacts where livingness is temporally displaced, such as those active only in production or degradation phases. Finally, while the lack of standardised terminology across disciplines posed challenges in search and selection, efforts were made to include studies from other fields and keep the keywords broad to mitigate this risk as much as possible.

Moving forward, several critical steps are necessary to deepen and validate these findings. Interviews with practitioners and academics, whose projects were used as case studies, will confirm and refine the definition of "living artefacts," illuminate the tools and processes used and identify promising future applications. On this regard, the definition will be evaluated and discussed with designers, HCI experts and bioengineers altogether. These insights will ground the research in real-world practice, uncovering the challenges and opportunities associated with working with natural, engineered and programmable materials.

Subsequently, a comprehensive "Design Process for Crafting Living Artefacts" will be developed. This process will integrate the three approaches into a cohesive framework, guiding designers and researchers in crafting artefacts that are living and regenerative. This flexible framework will navigate the complexities of working with living materials, from conceptualisation to user interaction, supporting the creation of artefacts that engage users and foster sustainable practices. The process will include ways to engage with users alongside the different phases.

In conclusion, this research positions living artefacts as a transformative design approach that integrates livingness to advance fields like design, HCI and material

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science. By embedding life-like qualities in artefacts, the study shifts design perspectives from static, human-centric views to dynamic, ecological approaches. The next steps will refine the theoretical foundation and develop practical tools, supporting the crafting of living artefacts capable of fostering sustainable, regenerative futures and advancing interdisciplinary discourse.

Supplementary material

The supplementary material for this article can be found at http://doi.org/10.1017/dsj.2025.10033.

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Competing interest

All authors declare that they have no competing interests.

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