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Societal implications of self-healing engineered living materials: insights from a co-design study

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Abstract

While Engineered Living Materials (ELMs) are increasingly investigated for technical viability, discussion of their broader societal implications remains limited. To address this gap, we conducted a multidisciplinary co-design workshop centred on a self-healing biomineralised bacterial cellulose (BMBC). Twenty participants from biodesign, bio-nanoscience, materials science and engineering worked in six groups through a three-phase process: (1) generating application concepts, (2) designing how self-healing would unfold and be experienced and (3) reflecting on ecological, social, economic and future implications. Workshop outcomes and discussions were analysed using thematic analysis. Participants framed self-healing not merely as functional repair but as temporal, expressive and relational transformation, emphasising personalisation, regeneration, trust and systemic embedding. The study demonstrates how early, material-led design exploration can surface societal dimensions before technical pathways stabilise. We argue that multidisciplinary co-design supports more responsible ELM development by revealing how such materials may function, be interpreted and acquire meaning in everyday contexts.

Impact statement

This paper contributes to the Biodesign community by offering pathways for the development of self-healing Engineered Living Materials, positioning anticipated societal implications as a central point of attention. It presents a design-led approach for unpacking these implications within multidisciplinary material development teams.

Introduction

Imagine a table that erases the scratches carved into the surface, removing them over the weekend. Or a climbing helmet that heals itself overnight, shifting in colour as it recovers. These scenarios help us consider how self-healing might be experienced and how it might reshape relationships between users and objects. They open up possibilities for creating more sustainable and responsive solutions. This study aims to uncover anticipated societal implications of self-healing Engineered Living Materials (ELMs) through the co-design of these scenarios within a multidisciplinary workshop.

ELMs are emerging hybrid materials that embed living cells into structural or functional matrices (Gilbert *et al.* 2021; Molinari *et al.* 2021; Nguyen *et al.* 2018). With advances in synthetic biology and materials science, these materials can grow, sense, adapt and repair themselves, promising new possibilities across construction to biomedicine (Lu *et al.* 2024; Srubar 2021). Specific examples include biomineralising building materials that embed bacteria to autonomously repair cracks (Heveran *et al.* 2020; Jonkers 2007), engineered fungal composites that retain living properties such as self-healing or responsiveness (Elsacker *et al.* 2023) and bacterial cellulose-based materials developed for biosensing, biocatalysis or structural applications (Gilbert and Ellis 2018).

Current research largely focuses on technical performance: enhancing robustness, efficiency and control. Yet as these materials move towards real-world integration, a new question arises: What implications do they entail for society? In this paper, we approach these concerns collectively as societal dimensions, referring to the ecological, economic, experiential and relational conditions through which ELMs become embedded in everyday contexts. Emerging work points towards societal challenges (Aleixandre *et al.* 2021; Ebbesen *et al.* 2024; Heveran *et al.* 2024). However, there remains a limited understanding of how diverse stakeholders involved in developing such materials consider and interpret these challenges.

Societal dimensions become particularly important when self-healing unfolds over time, leaves visible traces or behaves unpredictably. In such cases, it is not only a technical function, but also a process perceived and experienced by users. In this paper, we therefore approach self-healing not as a single technical mechanism, but as a broader class of material behaviours. These range from repair-oriented processes such as biomineralisation to more speculative and

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experiential forms of change, including growth, visible transformation or reconfiguration over time. From a design perspective, this positions self-healing as an expressive, temporal and relational process that shapes how materials are interpreted and engaged with, offering distinctive living aesthetics (Karana *et al.* 2020) that must be considered in the development of these materials. Bridging these aesthetic and expressive potentials with technical function and viability within multidisciplinary teams is therefore crucial when articulating the broader societal implications of emerging materials (Barati *et al.* 2019; Karana *et al.* 2015a)

To explore these societal dimensions of self-healing ELMs, we conducted a co-design workshop on biomineralised bacterial cellulose (BMBC) (Yu *et al.* 2021), used as a design probe to explore speculative self-healing scenarios. This ELM is currently under development by the research consortium (NextSkins 2026). Participants, from two research consortia, NextSkins (NextSkins 2026) and Fungateria (FUNGATERIA 2026), with different disciplinary perspectives, including biodesign, bionanoscience, materials science and engineering, were invited to design applications and self-healing behaviours and to reflect on societal implications, including user experience, ecological and economic impact. Rather than treating BMBC as a finished product, we used it as a design probe to investigate how participants engage with emerging material capabilities and how self-healing behaviours might be imagined for future application contexts.

This study makes three key contributions:

1. A set of design concepts that explore potential applications of self-healing ELMs;
2. Insights into how designers of ELMs shape self-healing as an expressive, temporal and relational process, resulting in a set of emerging design orientations;
3. Insights into anticipated societal implications of self-healing ELMs, as well as the further development trajectory.

Related work

Engineered living materials

ELMs are materials in which living cells function as structural or active components, enabling behaviours such as growth, regeneration, sensing and self-healing (Gilbert *et al.* 2021; Molinari *et al.* 2021; Nguyen *et al.* 2018). Situated at the intersection of synthetic biology and materials science, ELMs leverage biological processes to create responsive and adaptive material systems (An *et al.* 2022; Gilbert and Ellis 2018; Wang *et al.* 2025). Compared to conventional materials, ELMs can self-assemble, repair damage and interact with environmental stimuli (Rivera-Tarazona *et al.* 2021; Wang *et al.* 2022). Recent research has demonstrated their potential across domains, including biomedicine (Lavrador *et al.* 2021; Omer *et al.* 2022), environmental remediation (Datta *et al.* 2023; Wang *et al.* 2024), energy production (An *et al.* 2022; Yuan *et al.* 2025) and construction (Geng *et al.* 2024; Wang *et al.* 2025). Because ELMs rely on biological growth and self-regeneration, they are often positioned as promising contributors to sustainability, potentially reducing resource extraction and enabling circular material lifecycles (An *et al.* 2022). However, while their transformative potential is widely articulated, many ELM materials remain at relatively low technology-readiness levels, and their long-term environmental performance, scalability and lifecycle impacts require further investigation.

Recent trends in the field of ELMs include diversification of organism types, scaling from microscale to macroscale structures, and increasing emphasis on controllability, durability and functional optimisation (Gilbert and Ellis 2018; Lu *et al.* 2024). Despite these technical advances, translation beyond laboratory contexts raises new challenges. While scholars increasingly acknowledge ethical and societal questions surrounding safety, regulation and responsible innovation (Heveran *et al.* 2024), empirical and design-oriented investigations of these dimensions remain scarce. One of the few studies addressing public perception highlights the potential "yuck factor," suggesting that materials incorporating microorganisms may elicit affective responses such as disgust (Intemann *et al.* 2025), linked to concerns about contamination, naturalness and moral boundaries. Relatedly, Ertürkan *et al.* (2022) propose a vocabulary for describing living materials across technical, experiential and relational dimensions, reflecting growing recognition that ELMs require new language to articulate qualities such as agency and responsiveness. However, while such conceptual efforts offer important groundwork, systematic design research examining how these dimensions are interpreted and negotiated in practice remains limited. More broadly, integrating living systems introduces uncertainties regarding lifespan, maintenance, user trust and interpretability (Kleiner *et al.* 2025; Molinari *et al.* 2021). As a result, a gap persists between rapidly advancing technical capabilities and a deeper understanding of how ELMs might be meaningfully integrated into everyday contexts, particularly regarding how diverse stakeholders engage with these dimensions during development.

Social dimensions of emerging materials

Research across emerging material domains, including nanomaterials, smart and adaptive systems, and circular bio-based materials, demonstrates that material innovation reshapes not only technical performance but also ecological systems, economic structures, regulatory frameworks and everyday practices (Karana *et al.* 2015b; Poblete *et al.* 2024; Rosato and Triana 2025). In many cases, environmental risks, governance gaps and user-trust issues became visible only after materials were scaled up or embedded in products and infrastructure (Gottardo *et al.* 2021; Le *et al.* 2023; Linkov *et al.* 2015). These cases illustrate that material development is never purely technical, it reconfigures relationships between materials, users and institutions. In response, scholars argue that the implications of emerging materials should be explored during early development stages (Barati *et al.* 2019; Ferraro 2023; Wilkes *et al.* 2016).

Work on materials experience emphasises that sensory qualities, temporality and responsiveness influence how materials are trusted and integrated into practice (Karana *et al.* 2015a). Speculative and critical design approaches further demonstrate that engaging with emerging materials through artefacts and co-creation can surface ecological, socio-economic and future imaginaries before infrastructures stabilise (Tufail *et al.* 2023). These lessons are particularly relevant for living materials. Like other emerging materials, they promise sustainability and innovation while introducing uncertainties around safety, governance and adoption (Li *et al.* 2025; Tang *et al.* 2021) However, they have the ability to grow, self-repair or have other ongoing biological activities, which challenge assumptions of stability and control, foregrounding questions of agency, care and co-evolution (Zhou *et al.* 2024). In biodesign, such materials can be conceptualised as *Living Artefacts* that unfold over time and require relational

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engagement rather than passive use (Karana *et al.* 2020). Despite increasing recognition of these dimensions, structured design approaches for exploring social implications during early-stage ELM development remain limited. In this paper, we use the term societal dimensions to refer to the interconnected ecological, social, economic, experiential and future-oriented considerations that shape how emerging materials are interpreted, governed and integrated into everyday life.

Co-design workshops in multidisciplinary settings

Co-design has become a widely used approach for exploring emerging technologies, particularly when they introduce uncertainty, complexity or open-ended future implications (Avila-Garzon and Bacca-Acosta 2024). By bringing together participants from different disciplinary backgrounds, co-design workshops create structured environments for mutual learning, shared framing and collaborative concept development (Bisson and Perondi 2024; Penuel *et al.* 2022; Steen 2013; White *et al.* 2023). Rather than assuming a common language, such workshops function as translation spaces in which participants negotiate terminology, assumptions and problem framings across fields (Calvo and Sclater 2021; Nofal 2023). This quality is especially relevant for designing (with) emerging materials with unique temporal behaviour. In such settings, card-based design tools have been shown to support inclusive ideation and shared vocabulary development, helping to bridge considerations of temporal, functional and experiential qualities (Parisi *et al.* 2024).

In domains such as synthetic biology and smart materials, co-design workshops have been used to examine how novel systems might be interpreted, maintained or trusted before implementation (Huang *et al.* 2024; Kim *et al.* 2024; Moreira *et al.* 2023). For materials that may behave autonomously or appear "alive," such early dialogue becomes particularly important, as participants must collectively define what acceptable, meaningful or responsible behaviour entails (Elsacker *et al.* 2023; Kim *et al.* 2023). Building on this body of work, the workshop presented in this study engages multidisciplinary teams in collaboratively developing applications and expressive self-healing processes for an emerging ELM. The aim is not only to generate concepts but to facilitate shared articulation of material behaviour and its broader implications before technical pathways are fixed.

Methodology

Workshop context and aims

The co-design workshop was designed to explore how multidisciplinary teams engage with the design of an emerging self-healing ELM, in particular, how they conceptualise the application and expressive behaviour of a self-healing ELM, while also reflecting on its societal implications. The participants were recruited from two research consortia, NextSkins (2026) and FUNGATERIA (2026), which develop ELMs under the EU's EIC-Pathfinder Challenge funding scheme. Twenty participants were invited from these consortia to reflect a range of disciplinary perspectives, including biodesign, bio-nanoscience, material science and engineering. Approximately half of the participants had prior knowledge or work experience with the self-healing BMBC (Yu *et al.* 2021), which we used in the workshop. Prior to the workshop, a BMBC ELM material expert provided an introduction to this specific material, explaining its fabrication, properties and current and future capabilities. Furthermore, participants were able to touch and feel samples of the BMBC material. After that, participants were randomly assigned to six groups of three to four participants, ensuring that the backgrounds and two project consortia were mixed. The workshop was structured in three sequential phases: (1) concept development, (2) self-healing process design and (3) a group discussion on broader implications, to explore answers for the following research questions:

- What future concepts are developers of self-healing materials envisioning?
- What underlying motivations shape their imaginaries?
- What concerns and opportunities do they foresee for self-healing ELMs?

BMBC material and self-healing capabilities

The material used as a case in this study was an ELM currently under development in the EIC-Pathfinder research project NextSkins (2026). The base material, known as Biomineralised Bacterial Cellulose (BMBC), is a bio-composite inspired by nacre (Yu *et al.* 2021). It consists of biologically produced bacterial cellulose reinforced with calcium carbonate minerals through microbial activity. Based on the work of Yu *et al.* (2021), BMBC is strong, lightweight, impact- and fire-resistant and demonstrates high compressibility. It can be moulded, is biodegradable and is recyclable. In this study, self-healing was explored as a speculative extension of this material. The envisioned capability draws on microbial biomineralisation, a process in which microorganisms produce minerals that can strengthen or repair material structures, discussed as a promising pathway for regenerative and self-healing material futures (Vekemans *et al.* 2024). For example, dormant bacterial spores could be embedded within the material structure and activated by environmental triggers such as moisture or pH, initiating local mineral formation at damaged areas. While such self-healing behaviour is not demonstrated in the current BMBC material as described by (Yu *et al.* 2021), this envisioned capability served as a design case for the workshop.

Workshop procedure

Phase 1: concept development

This phase consisted of three rounds of ideation, in which groups generated and refined design concepts for the self-healing ELM. The first round lasted 8–10 minutes to familiarise participants with rapid brainstorming, followed by two shorter rounds of 5–7 minutes. Each round concluded with a concept, resulting in three distinct concepts per group by the end of the phase. After all three rounds, each group selected one of their three concepts and presented it in a short pitch to the plenary before further developing it in the following phase. In each round, participants received three design cards: a context card, a brainstorm card and an inspiration card. These cards were intended to provoke cross-domain associations and guide divergent thinking. A structured brainstorming canvas supported documentation of ideas, card selections and concept outcomes. For each round, one card from each of the three sets was randomly distributed to each group, allowing for diverse and unpredictable combinations (see Figure 1 for an impression of the co-design workshop during this phase). In the first two rounds, participants used general "What if?" brainstorm cards to stimulate divergent thinking. In the third round, these were replaced by a set of cards informed by the pillars of *Living Artefacts for Regenerative Ecologies* (Karana *et al.* 2023), to encourage participants to shift

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Figure 1. Impression of the co-design workshop, groups brainstorming about application concepts.

from object-scale functionality towards regenerative and ecosystem-oriented considerations.

Phase 2: self-healing design process

In this phase, each group selected one emotion card to frame the experiential qualities of their self-healing process. Participants were asked to design how healing would unfold over time in a way that evoked both a sense of livingness and the chosen emotion, acknowledging that ELMs exhibit dynamic, biologically driven behaviours rather than static repair. Before beginning the assignment, participants received a brief introduction to the X_Heal Toolkit (Vekemans *et al.* 2025), and its underlying taxonomy to ensure shared understanding of key structure and variables. Using the provided annotation template derived from the X_Heal Toolkit, groups were asked to design and document how self-healing would unfold over time. They specified changes in material variables (e.g., colour, texture, hardness, dimension) and temporal dynamics. Each group was given 15 minutes to complete the template. Afterwards, they delivered a pitch presenting their envisioned self-healing process and explaining how it would unfold and be experienced.

Phase 3: group discussion

The final phase consisted of a moderated plenary discussion among all participants, focused on the ecological, societal and future-oriented dimensions of self-healing ELMs. Each thematic topic was discussed for approximately 10 minutes. Each group was invited to reflect on their concept in response to three guiding questions:

1. How would your concept interact with and affect the environment at various stages of its lifecycle (e.g., during use and at the end of its life)?
2. What are the main challenges (technical, economic or societal) that could influence the feasibility and acceptance of your concept? How might these be addressed?
3. How do you imagine your concept evolving over the next 20 years? Consider environmental impact, technological advancements and societal needs.

Probes in the co-design workshop

Since not all participants were trained in iterative design or creative brainstorming methods, the workshop incorporated structured probes to support inclusivity, stimulate imagination and facilitate shared understanding across disciplines. Four types of cards were developed: context cards, inspiration cards, brainstorm cards and emotion cards. The design of these probes was informed by literature on co-design, speculative design and design fiction, which use structured prompts to provoke cross-domain associations and challenge existing assumptions (Halskov and Dalsgård 2006; IDEO 2015; Peters *et al.* 2021; Roy and Warren 2019).

The context cards introduced broad, material-relevant application domains in which materials are intensively used, exposed or embedded in everyday life and infrastructure. The selected domains spanned indoor and outdoor settings, ranging from personal-scale applications (e.g., wearables) to infrastructural contexts (e.g., mobility and transportation) and extreme environments, and were intentionally broad and not exhaustive to stimulate diverse interpretations across personal, societal and ecological scales. Inspiration cards were curated across three domains: nature, science fiction and materials science, each including a short description and visual example to support both functional reasoning and imaginative envisioning. The brainstorm cards consisted of open-ended "What if?" prompts designed to stimulate divergent thinking (Board of Innovation 2026; Peters *et al.* 2021). The eleven prompts used in the first two rounds addressed experiential, configurational and economic dimensions (e.g., surprise, sharing, rental models). In the third ideation round, five prompts informed by the Living Artefacts for Regenerative Ecologies framework (Karana *et al.* 2023), intentionally shifted the focus from product-level functionality to ecosystem-level, relational and regenerative thinking.

The emotion cards were derived from two complementary affect classification models (Barrett and Russell 2014; Desmet 2018), combining dimensional accounts of affect (e.g., valence and arousal) with discrete emotion categories (e.g., joy, pride), thereby offering both structured and interpretable emotional framings. Some overlap between categories was intentionally retained to allow interpretative flexibility and enable different groups to explore related affective qualities from distinct angles. The probes were iteratively refined through collaborative discussions among the authors and piloted in a rehearsal session prior to the workshop to assess clarity, timing and usability.

In addition to the cards, a structured A3 brainstorming canvas was developed to scaffold documentation and iterative concept development, supporting visual and verbal articulation across

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disciplines (Medeiros Leopoldino *et al.* 2017). To guide the detailed articulation of self-healing processes, participants used the X_Heal Toolkit, developed in prior design research as a structured framework for analysing and characterising dynamic, temporal self-healing behaviours in living materials (Vekemans *et al.* 2025). Before engaging with the toolkit, participants received a brief introduction to its underlying taxonomy and an example application to ensure shared understanding of key variables such as colour, texture, hardness, dimensional change and temporal dynamics. This enabled participants to specify perceptible transformations and healing trajectories in a systematic and comparable manner. An overview of all materials is provided in Table 1. Representative visual examples of the probes are included in Appendix A, and the full set of brainstorm prompts is listed in Appendix B.

Data collection and analysis

The collected workshop data included brainstorming canvases, X_Heal Toolkit annotation templates, concept sketches and descriptions, as well as transcriptions of team pitches and the final plenary discussion. Figure 2 provides representative examples of completed brainstorming canvases from Round 1 of the workshop, illustrating how participants documented ideas, card combinations and emerging concepts. Figure 3 presents two completed X_Heal Toolkit annotation templates, demonstrating how temporal changes and material variables were specified during the self-healing design phase. Together, these materials comprised visual and verbal representations of participant thinking. A two-part thematic analysis (Braun and Clarke 2006) was conducted to examine (1) the design modes and orientations that emerged during the workshop and (2) the reasoning participants used about the future implications of self-healing ELMs.

Application concepts and self-healing processes analysis

The first author conducted a thematic analysis of the concept development and self-healing design phases (Phases 1 and 2). Patterns were identified in the types of problems addressed, envisioned transformations and interpretations of self-healing behaviour. These insights were iteratively clustered into recurring design modes and orientations, supported by visual and textual evidence. The second author contributed to discussions during the clustering and refinement process to ensure thematic clarity and alignment with workshop objectives. Concept visualisations were generated by the first author using an AI image generation model (OpenAI 2026) and iteratively refined through prompt engineering.

Discussion analysis on implications

A separate thematic analysis was conducted of the Phase 3 group discussion, focusing explicitly on the ecological, technical and social, and future-oriented implications of the designed concepts. This analysis was conducted collaboratively by the first author and two co-authors. In the first round, each researcher independently reviewed the full transcript and generated preliminary codes. These codes were then discussed collectively to identify overlaps, resolve interpretive differences and agree on a set of final themes. A second round of refinement was undertaken by the first author in collaboration with the second author, during which codes were consolidated and themes structured into coherent clusters. A final iteration was reviewed with the last author to finalise theme labels and section structure. This multi-stage, collaborative process ensured analytical rigour through investigator triangulation (Carter 2014), enabling multiple interpretive lenses to inform the final thematic framework.

Results

Application concepts & self-healing processes

During the workshop, six multidisciplinary teams developed application concepts for the self-healing material BMBC. Across three ideation rounds, each group generated multiple concepts and selected one to further elaborate and present to the plenary. The concept titles were defined by the participants during this process. In the second phase, groups articulated a detailed self-healing process for their selected concept, guided by a chosen emotion as an experiential lens and by an intention to evoke a sense of livingness in the material behaviour. Using the X_Heal annotation template (Vekemans *et al.* 2025), they specified temporal dynamics and changing material variables (e.g., colour, texture, hardness, dimension). The resulting six concepts, including their participant-defined titles, articulated self-healing processes, selected emotions and representative participant quotes, are presented in Table 3.

Modes of self-healing and design orientations

Our analysis revealed that the concepts of participants reflected different modes of self-healing, which varied according to the intended context and application. While not mutually exclusive, these modes structured the form, timing and user-material relationship of the self-healing process. By structuring and analysing variations in concepts and self-healing processes, we identified four modes of self-healing, which are presented in Table 2.

Through thematic analysis, we identified five common design orientations present in both the concepts and self-healing processes. These orientations reflect how participants reasoned about when self-healing occurs, how it unfolds over time, what changes are made visible and how users relate to and intervene in the process.

Tackling material problems through regeneration and replacement

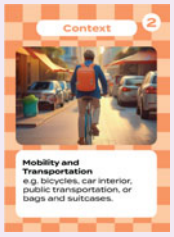
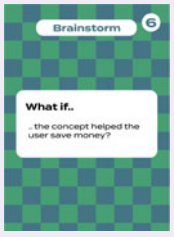
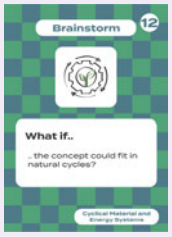
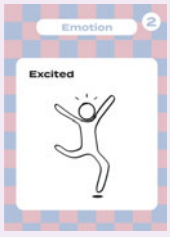
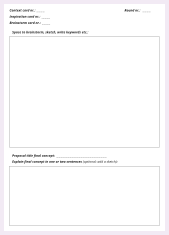
Several concepts were grounded in pragmatic concerns such as durability, waste or environmental degradation. Self-healing was positioned as a functional solution to common material failures, particularly those linked to unsustainable practices or frequent replacement. For example, *Endless Chalk* addressed chalk breakage and consumption in classrooms, proposing a material that regrows and reduces waste. *Biodegradable Golf Ball* replaced conventional plastic-based golf balls, offering both biodegradability and self-regeneration. The *Regenerative Protective Helmet* removed the need to discard protective gear after a single impact, extending its lifespan.

Designing for growth, personalisation and co-evolution

Other concepts foregrounded the capacity of ELMs to grow and change alongside users. In these cases, self-healing was framed as a medium for emotional expression, memory and customisation rather than merely structural repair. The *Growing Desk* was imagined as evolving over time, retaining traces of use and gradually becoming personalised through interaction. The *Regenerative Protective Helmet* visualised its healing process through colour shifts, embedding use history into the object and making repair perceptible. The *Endless Chalk* regenerated in playful forms and changing colours, inviting joyful engagement.

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Table 1. Overview of design probes and materials used in the co-design workshop

Visual example	Probe	Composition	Examples	Role in workshop	Phase
	**Context cards**	Eight broad material-relevant application domains spanning indoor and outdoor contexts.	Mobility and transportation; wearables; home and living spaces; education and learning.	Anchored ideation in contexts where materials are intensively used or exposed, while enabling cross-scale exploration across personal, societal and ecological settings.	Phase 1
	**Inspiration cards**	Three domains × five cards each; short description + visual example.	Nature (e.g., lizard tail regeneration); science fiction (Terminator); materials science (e.g., self-healing foams and rubber).	Balanced empirically grounded precedents with speculative imaginaries to support both functional reasoning and imaginative projection	Phase 1
	**Brainstorm cards** (general)	Eleven open-ended "What if?" prompts.	"What if the concept gave the user something unexpected?" "What if the concept went from ownership to rental?"	Encouraged unconventional problem-solving across experiential, economic and systemic dimensions.	Phase 1 (Rounds 1–2)
	**Brainstorm cards** (Living Artefacts for Regenerative Ecologies)	Five prompts informed by Living Artefacts for Regenerative Ecology framework.	"What if the concept could fit in natural cycles?" "What if the concept fosters different life forms?"	Shifted focus from object-level repair to ecosystem-level, relational and regenerative dynamics.	Phase 1 (Round 3)
	**Emotion cards**	A set of 26 emotions combining dimensional (valence/arousal) and discrete categories.	Joy; pride; calm; bored; alert; excited; shame; tense; hope.	Helps to frame self-healing as an experiential, perceptible and interpretative process.	Phase 2
	**Brainstorming canvas**	Custom A3 worksheet including designated fields for card codes, sketch space, annotations and a final concept section for each round.	Designated fields for card identifiers; open space for brainstorming, sketching and annotation; and a structured section for final concept articulation and naming.	Structured documentation of ideation trajectories, enabling traceability across rounds and supporting both visual and verbal articulation across disciplines.	Phase 1

(*Continued*)

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Table 1. (*Continued*)

Visual example	Probe	Composition	Examples	Role in workshop	Phase
	**X_Heal toolkit**	Annotation template, a filled-in example and taxonomies for specifying temporal and variables for self-healing processes and material change.	Self-healing direction and speed; visible, form or tactile change (e.g., rough to smooth, colour change, dimensional growth).	Enabled systematic articulation of dynamic and perceptible self-healing processes.	Phase 2

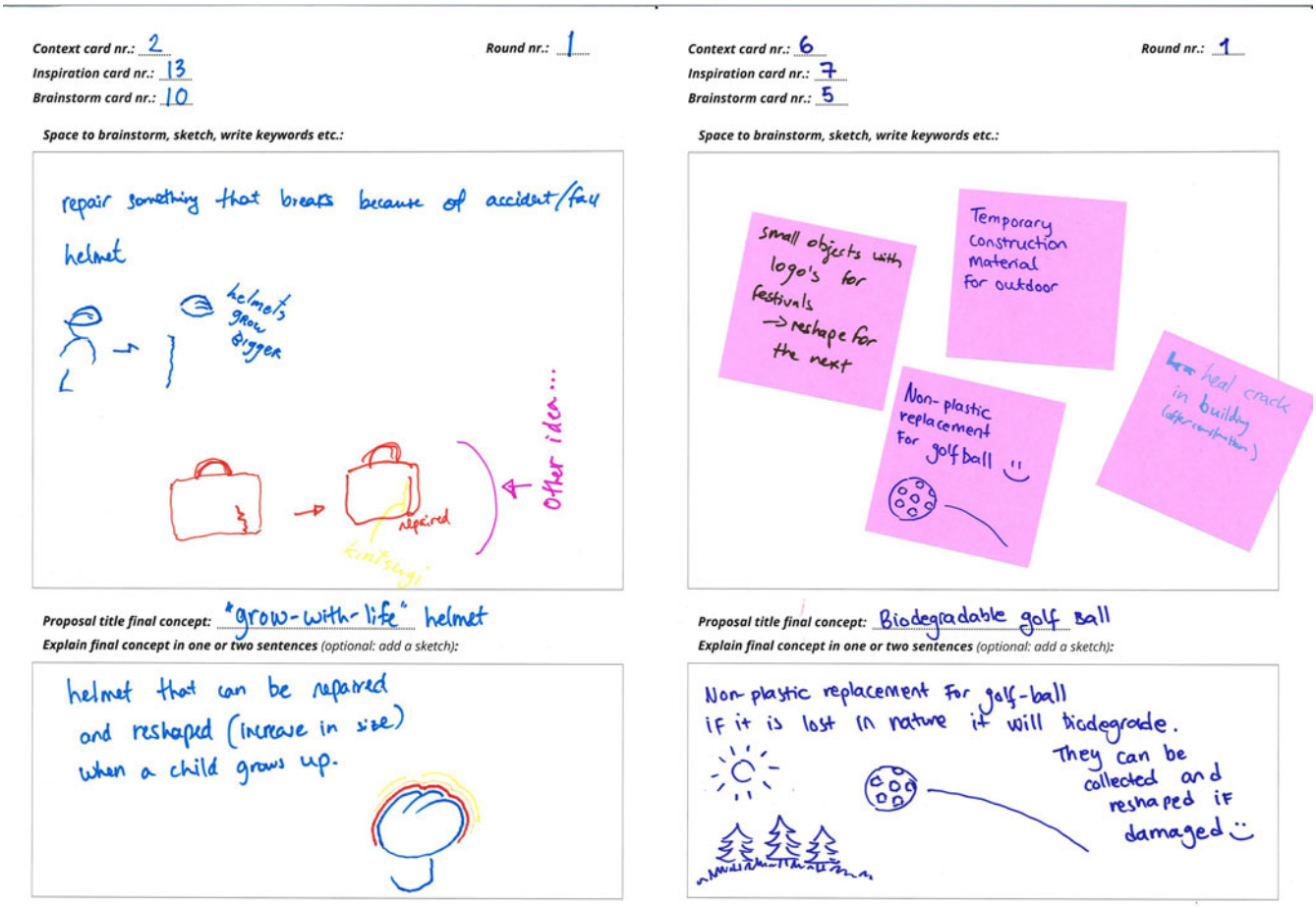


Figure 2. Two filled-in Brainstorming Canvases of two different groups during the co-design workshop, round 1.

Self-healing as transformation, not just repair

Some groups conceptualised self-healing not as a return to an original state, but as a transformation. Damage was treated as a generative condition, an opportunity for the material to evolve rather than a defect to erase. The *Biodegradable Golf Ball*, for instance, regenerated into a ball with altered colour and texture, remaining functional but no longer identical to its previous form. The *Growing Desk* retained and modified scars over time, allowing meaning to persist and gradually shift. In the *Coral Shelter*, regeneration was followed by densification, resulting in a structure that could become stronger than before.

Cooperative and environmental interactions

In several concepts, self-healing was imagined not as an isolated material response but as a process emerging through interaction with broader systems. Self-healing was situated within ecological, environmental and interspecies dynamics. The *Coral Shelter* relied on other organisms to germinate spores and regenerate damaged structures, functioning as part of an ecological collective. The *Fix It Pole* adapted to urgent needs in outdoor contexts, such as canoe repair, responding to environmental circumstances and user intervention. The *Growing Desk* was envisioned as ageing and adapting in response to its surroundings, including light and environmental

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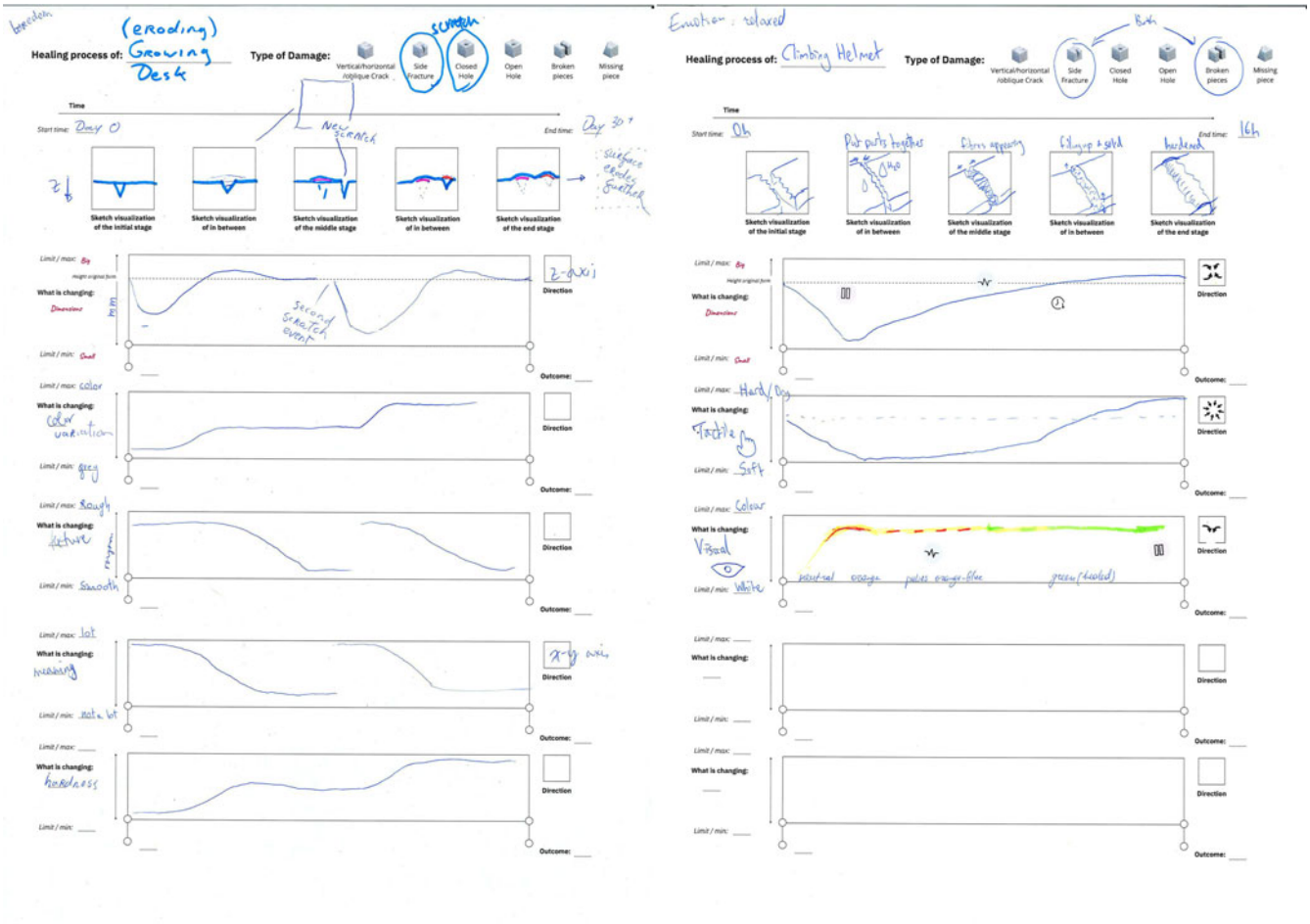


Figure 3. Two completed X_Heal Annotation Templates from two different groups during the co-design workshop, phase 2.

Table 2. Modes of self-healing across concepts

Modes	Description	Example concept
Remoulding	User reshapes or activates material directly.	*Fix it Pole*; *Regenerative Protective Helmet*
Biological growth	Healing unfolds autonomously via living processes.	*Coral shelter*
Autonomous regeneration	Healing activates without user input and regenerates over time.	*Biodegradable golf ball; growing desk*
Interactive regenerative growth	Healing emerges through use/play patterns.	*Endless chalk*

conditions. These concepts reframed the material not as a passive object but as an actor embedded within a larger ecology.

Temporalities of self-healing and perceivable change

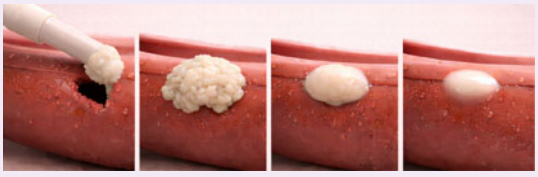
Across all concepts, self-healing was designed as a temporal process rather than an instantaneous event. Self-healing unfolded over varying durations, from one to two hours (*Fix it Pole*) to approximately 16 hours (*Regenerative Protective Helmet*), and up to 30 days (*Growing Desk*, *Coral Shelter*). In some cases (*Biodegradable Golf Ball*, *Endless Chalk*), duration was left unspecified. Importantly, time was closely synchronised with perceivable material change. Self-healing was rarely imagined as invisible. Instead, participants designed changes in colour, texture, hardness, stiffness or form to communicate different stages of repair. In the *Regenerative Protective Helmet*, colour oscillations signalled activation and completion. In the *Growing Desk*, slow smoothing and colour saturation evoked memory and gradual strengthening. The *Coral Shelter* marked regeneration through densification and chromatic variation. The *Biodegradable Golf Ball* and *Endless Chalk* framed healing as transformation, emphasising new layers, altered textures or emergent shapes. In the *Fix it Pole*, rapid expansion and hardening made the repair visibly functional within an urgent context.

On the anticipated implications of self-healing ELMs

Following the pitches of the design concepts and their associated self-healing processes (Phase 1 and 2), participants engaged in a collective discussion to reflect on the anticipated implications of the proposed applications. Reflections moved fluidly across environmental concerns, social expectations, technical constraints and imagined futures, often addressing multiple dimensions simultaneously. The discussion transcripts were analysed using thematic analysis (Braun and Clarke 2006), resulting in the identification of three interrelated clusters of implications:

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Table 3. Overview of six concepts and their articulated self-healing processes developed during the co-design workshop. Concept visualisations were generated by the first author using openai_dalle_2026 based on the descriptions of participants

Title & Visual	Concept & Self-healing Process	Emotion & Quote
Growing Desk 	*Concept:* A living desk surface designed for children that accumulates scratches and marks through daily use and regenerates during periods of rest (e.g., weekends or holidays). The desk is intended for long-term use, being able to grow with the user, embedding traces of activity over time. *Self-healing process:* Healing unfolds gradually (>30 days) and may repeat in the same area. Surface texture shifts from rough to smooth, hardness increases with each cycle, and colour transitions from grey to more saturated tones. Rather than instant restoration, physical traces and their associated meanings fade progressively.	*Emotion:* Boredom *Quote: "A landscape of different meanings, different textures."*
Endless Chalk 	*Concept:* A regenerating classroom chalk inspired by biological regrowth, designed to reduce breakage and waste in educational settings. Pigments allow it to respond to environmental conditions for colour change. *Self-healing process:* After damage, the chalk regrows in playful shapes and shifting colours. It becomes temporarily softer and lighter; rough → smooth over time, weight and hardness temporarily decrease, and the material may not fully recover its original hardness.	*Emotion:* Joy *Quote: "We get the joy in the way of growing a weird shape, like a lollipop."*
Fix it pole 	*Concept:* A multifunctional outdoor pole that can be remoulded to serve emergency or recreational purposes (e.g., fishing or tent support). *Self-healing process:* A soft insert is activated and expands to fill gaps within 1–2 hours. Hardness increases as the material integrates; texture smooths; glossiness shifts from matte to glossy, forming a protective, water-resistant layer. Healing is rapid, user-initiated and functionally restorative.	*Emotion:* Pride *Quote: "It also goes from matte to glossy because you get the protective layer on top that protects it from humidity."*
Coral shelter 	*Concept:* A marine shelter inspired by coral reefs, designed to support biodiversity and ecological balance. Healing is triggered by organisms that help to inniate the regrowth of the missing parts. *Self-healing process:* Damage triggers organism-supported regrowth over ˜30 days while remaining functional. Dimension increases through regrowth, followed by densification that raises stiffness and strength. Colour shifts from dark to lighter tones and back.	*Emotion:* Alert *Quote: "Then there would be another densification step, so this area becomes even stronger than before."*
Biodegradable golf ball 	*Concept:* A biodegradable golf ball that heals cracks during use and decomposes when lost in nature. Under extensive damage, it forms a new ball. *Self-healing process:* Cracks are filled internally, followed by growth of a new outer layer. Dimension and surface texture change; colour shifts visibly. The regenerated ball differs from the original in colour and texture, it transforms into a new version/object.	*Emotion:* Hope *Quote: "It actually forms a new layer, a new ball with a new colour, new texture going from rough to smooth and a new colour going from purple to blue."*
Regenerative Protective Helmet 	*Concept:* A climbing helmet designed to self-heal after impact, removing the need for replacement while maintaining protective function. *Self-healing process:* Upon water activation, fibres reconnect fractured parts over ˜16 hours. The outer shell hardens while the core remains slightly softer. Colour shifts (white → orange, oscillating yellow-orange, finished → green) communicate healing stages, embedding repair within a temporal routine.	*Emotion:* Relaxed *Quote: "He will set it aside, make some tea by the campfire and get the process going."*

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(1) ***Ecological Aspects***, (2) ***Social, Economic and Technical Implications*** and (3) ***Development Trajectories for self-healing ELMs***. This means the final themes were reframed to reflect cross-cutting patterns in how participants articulated materials experience, systemic considerations and future imaginaries. These clusters reflect recurring concerns, opportunities and speculative directions raised when considering the integration of self-healing ELMs into everyday contexts (see Appendix C for an overview of the thematic analysis table). In the following section, we elaborate on the themes, associated subthemes and subtopics identified through our analysis, situating them within and beyond the context of self-healing ELMs.

Ecological implications of self-healing ELMs

Participants discussed ecological implications primarily through two subthemes: **Uncertainty** and **Diverse narratives**.

- Uncertainty

A recurring topic was uncertainty about **emissions and material release**. Participants questioned how substances involved in the self-healing process (e.g., ammonia, calcium, calcite) might interact with ecosystems, especially in sensitive natural contexts, such as the proposed *Coral Shelter* concept. Ecological uncertainty was further articulated as **context-dependent**. Participants distinguished between closed, domestic environments and open, natural contexts and discussed how risks might differ across these contexts. Concerns about exposure were particularly salient in scenarios involving children, for example, in relation to the *Endless Chalk* or *Growing Desk* concepts, including accidental ingestion or frequent touch. In addition to concerns about emissions, participants also speculated on how **environmental exposure** might affect the material itself over time. Rather than framing this solely as degradation, some described environmental interaction as a visible and meaningful transformation, for example, when the *Regenerative Protective Helmet* was imagined to "age" through colour shifts as part of its healing cycle.

- Diverse narratives

Alongside uncertainty, participants articulated different narratives for framing sustainability. One common comparison was between the proposed living material and fossil-based plastics, in which participants described BMBC-based concepts as **natural replacements** and self-healing processes as closer to "natural" ones. Another recurring framing focused on **lifecycle extension**, in which participants described remoulding and reshaping as mechanisms that enable objects to persist for long periods, thereby reducing material replacement. However, this was often framed as harm reduction rather than ecological regeneration. One participant explicitly noted that the benefit lay not in positive regeneration, but in "the absence of things that are worse."

Experiential, economic and techno-functional implications

Participants discussed feasibility and acceptance through intertwined considerations rather than separating "social," "economic," and "technical" into distinct areas. Three interrelated subthemes were identified: **Trust**, **Experiential value** and **Techno-economic systems**.

- Trust

Trust emerged as a foundational condition for the acceptance of self-healing ELMs through our study. Participants consistently framed **safety** as a requirement, particularly in applications involving children, such as the *Growing Desk* and *Endless Chalk* concepts. In these contexts, acceptance was not seen as an individual choice but as a matter of responsibility, with parents as decision-makers. Beyond safety, trust was challenged by uncertainties regarding the reliability of materials after healing. Participants questioned whether repaired or regenerated materials would be trusted to perform as intended, focusing on **functionality**, especially in safety-critical contexts such as protective equipment, for example, in the *Regenerative Protective Helmet* or the *Fix It Pole* when used in emergency repair situations. Even when healing restored form or function, participants suggested that confidence might not be automatically regained. Concerns about trust were further addressed by perceptions of material autonomy and loss of control. Participants expressed discomfort with materials that heal or grow without explicit user intention, raising questions about predictability and **material agency**. Remarks such as "You wake up, and your house is full" and "What happens if it self-heals when I don't want it to?" reflect anxieties about **unwanted or excessive material behaviour**. At the same time, participants identified **familiarisation** over time as a possible pathway to trust. Exposure through low-risk, everyday contexts, such as classroom use of *Endless Chalk*, particularly with young children, was framed as a means of normalising self-healing behaviours and gradually building acceptance.

- Experiential value

In parallel with concerns about trust, we identified multiple forms of **experiential value** associated with self-healing ELMs through our study. **Aesthetic appeal** was highlighted as a key driver of desirability. Rather than being only perceived as a maintenance function, self-healing was framed as a potential unique selling point, capable of differentiating products through **aesthetic adaptation**, such as visible transformations and regeneration over time, as exemplified by the *Regenerative Protective Helmet*'s staged colour shifts and the *Biodegradable Golf Ball*'s transformation into a visibly altered new version. Self-healing was imagined as enabling surfaces or forms to be refreshed, reconfigured or renewed in response to changing preferences, trends or seasons. **Interaction** and **performativity** could also play a central role in the appeal of self-healing materials. Damage and repair were not always seen as negative events, but as opportunities for expression and personalisation, for instance in the *Regenerative Protective Helmet*'s visible healing cycle or the *Growing Desk*'s gradual transformation of scratches into evolving surface patterns.

- Techno-economic systems

Through the reflections, a recurring tension emerged between relationship **durability and sales logic**. Highly durable, self-healing products could challenge replacement-based economic models. Participants questioned how such products could fit within current market structures and whether people would be willing to invest in a product that everyone buys and no one buys again. At the same time, participants identified contexts in which self-healing aligns with established economic practices. In domains involving expensive or long-lasting products, such as cars, buildings or large equipment, maintenance is already an accepted norm and has **repair as a value proposition**. In these cases, self-healing can be framed as a logical extension of existing value propositions rather than a disruption. **Service-based and subscription models** were proposed as one way

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to combine durability with economic sustainability. Technical feasibility also emerged as a constraint within these discussions. Participants questioned whether there would be **demand or necessity** for self-healing ELMs, as there are already products made from materials that "do the job." To that end, **high material costs** were identified as a concern.

Development trajectories

In the final part of the plenary discussion, participants reflected on how self-healing ELMs and their associated concepts might evolve over the next 20 years. These reflections extended beyond immediate feasibility and focused on possible long-term transformations in how ELMs could function and relate to users and environments. Three subthemes were identified: **Biological Computers**, **Programmability** and **Co-evolution with Users and Environments**.

- Biological Computers

Participants envisioned future self-healing ELMs as part of bio-digital or bio-electrical infrastructures, in which biological processes function as communication, sensing or signalling mechanisms. Rather than relying on conventional electronic components, living organisms and microorganisms were imagined as integral to how materials interact with their surroundings and with other devices. In this trajectory, biological signalling, such as quorum sensing or bioluminescence, was described as an alternative mode of interaction comparable to wireless or digital communication systems. Participants speculated about materials that could signal states such as charging, damage or activity through biological responses rather than screens or indicators.

- Programmability

A second development trajectory focused on the programmability and upgradability of self-healing ELMs. Participants frequently drew analogies to digital systems, particularly software updates, to describe how living materials might gain new capabilities over time. In this framing, materials were imagined not as static objects, but as systems that could be extended, modified or reconfigured after deployment. Participants described scenarios in which materials receive "updates" that activate new functions, such as sensing, interaction or energy transfer. In some cases, programmability was linked to interface-like mechanisms that allowed users to intentionally trigger changes through external inputs or purchases. For example, participants imagined acquiring specific capabilities that enable materials to morph into different forms or styles, drawing parallels to digital filters or downloadable content.

- Co-evolution with Users and Environments

The third development trajectory focused on co-evolution with users and environments. Participants framed materials as having a degree of agency, capable of adapting, mutating or growing over time rather than remaining fixed. At the user level, co-evolution was associated with **personalisation through growth**. Participants imagined products that grow with users, for example, the *Regenerative Protective Helmet*, to reflect individual identities and accumulate traces of interaction over time, as illustrated by the *Growing Desk*. This ongoing adaptation was linked to increased care and emotional attachment, as materials become specific to a person or context rather than interchangeable. At the environmental level, participants extended this idea to climate and ecological change and described **material adaptation**. Materials were envisioned to adapt their appearance or properties in response to long-term environmental shifts, such as changes in temperature or humidity. In the end, a participant further described living materials as **relational entities** and reframed the materials as companion species.

Discussion

We discuss the findings through the lens of our three research questions: (1) what future concepts developers envision for self-healing ELMs, (2) what motivations shape these imaginaries and (3) what concerns and opportunities they foresee for integration into everyday contexts. We then reflect on how these findings invite a reframing of "self-healing" within ELM research and reflect on the methodology. In the end, we discuss limitations and directions for future work.

Envisioned futures: how developers imagine self-healing ELMs

Across the six concepts, participants envisioned self-healing ELMs not as a single repair function but as diverse future material roles. In safety-critical applications such as the *Regenerative Helmet*, healing ensured protective continuity by restoring structural integrity after impact. In the *Fix It Pole*, self-healing enabled adaptive versatility, allowing the material to shift from soft and mouldable to hard and stable in response to situational demands. Other concepts emphasised transformation rather than strict restoration: both the *Growing Desk*, the *Endless Chalk* and the *Biodegradable Golf Ball* incorporated visible change, altered material qualities or the formation of new layers, suggesting that healing could produce difference rather than return to an original state. In ecological applications such as the *Coral Shelter*, regeneration was imagined as distributed across organisms and environment, where damaged structures not only regrew but sometimes densified and strengthened within a broader ecosystem. Taken together, these orientations suggest how participants, as developers of ELMs, imagine self-healing less as a technical upgrade and more as a situated capability shaped by context, value systems and intended relationships between materials, humans and broader ecological systems.

At the level of agency, the identified self-healing modes span a spectrum from user-activated remoulding to autonomous biological regeneration and interactive growth. This spectrum aligns with perspectives in materials-oriented (interaction) design that frame materials as active participants in interaction rather than passive substrates (Karana *et al.* 2015a; Parisi and Rognoli 2016; Vallgårda and Redström 2007). The longer-term trajectories further extend these imaginaries towards programmable, bio-digital and co-evolving infrastructures (Breed *et al.* 2026; Rotondi 2023; Tang *et al.* 2021; Walther 2020). Together, these findings suggest that participants imagine self-healing ELMs as future-facing material systems that reframe how durability, interaction and environmental participation are understood (An *et al.* 2022; Elsacker *et al.* 2023; Nguyen *et al.* 2018).

Motivations behind imagineries

The futures imagined by participants were shaped by three recurring motivations: resource continuity, experiential meaning-making and relational embedding. First, self-healing was framed as a response to disposability and material waste, positioning durability and lifecycle extension as central values. Sustainability,

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however, was not assumed to be inherent. Ecological benefits were treated as conditional and context-dependent, aligning with calls for lifecycle-oriented and Safe and Sustainable by Design approaches (Cassee *et al.* 2024; Salieri *et al.* 2021; Subramanian *et al.* 2023). Second, self-healing was often designed to be perceptible and expressive. Rather than concealing repair, participants staged visible transformations, scars and colour shifts, suggesting that living material change can function as a meaningful trace of interaction, as earlier motivated by Groutars *et al.* (2022) with the concept of *living traces* with Flavobacteria. This resonates with *material traces* perspectives in design research, where wear and transformation become inscriptions of use rather than defects (Gill and Lopes 2011; Lilley *et al.* 2019; Rosner *et al.* 2013). Third, self-healing was embedded within ecological and more-than-human relations, particularly in concepts that distributed regeneration across organisms and environments. This resonates with recent approaches in biodesign that foreground multispecies orientations, ecological sensibilities and inclusive modes of thinking when designing with living organisms (Bell *et al.* 2024; Groutars *et al.* 2024; Ikeya *et al.* 2023; Kim *et al.* 2024; Zhou *et al.* 2024). These layered motivations indicate that imaginaries of developers are shaped not only by technological novelty but also by values of durability, expressiveness and inclusivity.

Concerns, conditions and systemic tensions

Alongside these motivations, participants articulated anticipated concerns and systemic conditions shaping the feasibility of self-healing ELMs. Three interrelated challenges emerged: trust and legibility, ecological uncertainty and techno-economic alignment. Trust was foundational. Participants questioned safety, reliability after healing and unwanted autonomy, suggesting that self-healing must operate as a communicative process as much as a mechanical one. Visible and staged healing, therefore, becomes not only expressive but necessary for interpretability and accountability. Ecological sustainability was similarly treated as conditional rather than guaranteed. Participants critically questioned emissions, exposure and deployment contexts, indicating that "naturalness" does not equate to harmlessness (An *et al.* 2022; Ebbesen *et al.* 2024). At the economic level, durability was recognised as potentially disruptive to replacement-driven business models, prompting speculation about service and stewardship-oriented alternatives (Bocken and Short 2016; Han *et al.* 2020). These concerns were not framed as reasons to reject self-healing, but as systemic conditions that must be addressed. Participants identified opportunities in durability, new experiential engagements and ecological regeneration imaginaries, yet their realisation depends on governance structures, lifecycle assessment and economic models capable of supporting long-term material relationships.

Rethinking self-healing in ELMs

A key contribution of this study is demonstrating that, in early-stage multidisciplinary exploration, self-healing is not treated as a stable engineering category but as a design space. Rather than being defined solely by mechanical recovery or biological functionality, self-healing was articulated through (1) configurations of agency, (2) temporal and perceptible material change and (3) relational and systemic embedding. In this framing, self-healing shifts from hidden restoration to staged regeneration, in which transformation becomes intertwined with interpretation, care and responsibility. The *Regenerative Protective Helmet* illustrates this shift particularly clearly. Healing was designed as a 16-hour colour oscillation embedded within a camping routine, transforming repair into an experiential event. Rather than merely returning the helmet to its prior state, the process produced visible anticipation and meaning. This resonates with Living Artefacts that conceptualise living materials as evolving artefacts embedded in experiential and ecological relations (Karana *et al.* 2020; Karana *et al.* 2023). In this study, these insights are articulated as descriptive patterns and emerging design orientations derived from the workshop, rather than as a formalised framework or validated taxonomy.

Much ELM research has emphasised performance optimisation, which often treats self-healing as a measurable return to a predefined original state. From an ELM development perspective, our study implies that evaluation cannot remain limited to mechanical recovery metrics alone. Legibility, acceptable autonomy, experiential coherence and contextual sustainability emerge as equally relevant dimensions. This reframing shifts self-healing from a performance indicator to an interactional and systemic design question. For ELM research and development, this motivates earlier integration of design-led exploration alongside laboratory optimisation.

Reflection on our methodology

Beyond generating application concepts, the co-design workshop positioned materials experience itself as a site of inquiry. By requiring participants to specify how self-healing unfolds, its duration, visibility, colour changes and tactile changes, the process foregrounded perceptual and temporal qualities as primary design variables rather than secondary effects. The discussion, therefore, shifted from "Can the material heal itself?" to "How is self-healing perceived, interpreted, and trusted?". The use of emotion cards and the X_Heal Annotation Template (Vekemans *et al.* 2025) structured this process. As a result, colour oscillations, hardening phases and scar retention were not incidental details but became central to later discussions on trust, agency and desirability. This means that experiential ideation functioned as an anticipatory method, surfacing social, ecological and systemic implications before technical pathways stabilised. The inclusion of Living Artefacts for Regenerative Ecologies brainstorm cards encouraged participants to consider the environmental and relational dimensions of self-healing. This enriched sustainability-oriented reflections and illustrates how methodological scaffolding can orient co-design discussions towards particular thematic directions. In this sense, the workshop highlights both the generative and formative role of structured probes in shaping how emerging materials are imagined and framed.

Limitations and future work

This study has several limitations that should be taken into consideration when interpreting the findings. Participants engaged with physical samples of the material. However, the self-healing mechanism itself was still under development and could not be demonstrated during the workshop. As a result, self-healing processes were envisioned based on projected capabilities rather than direct observation. Furthermore, the study focused on a single emerging material (self-healing BMBC). While this enabled in-depth exploration, other ELMs may exhibit different behaviours, constraints, governance challenges or ethical considerations. Replicating similar co-design approaches across diverse ELMs would clarify whether comparable design orientations and

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implication patterns emerge, or whether imaginaries vary substantially across biological platforms.

The workshop was deliberately designed to address multiple dimensions of implications simultaneously, including ecological, experiential and socio-economic. Although this breadth enabled a holistic exploration, it limited the depth with which any single dimension could be examined. Future research could therefore adopt a more focused lens, for example, investigating affective and trust dynamics in detail (Intemann *et al.* 2025; Moreira *et al.* 2023), analysing techno-economic feasibility and governance structures (Heveran *et al.* 2024; Srubar 2021) or conducting lifecycle and environmental assessments tailored to specific material systems (Aleixandre *et al.* 2021; An *et al.* 2022). Such targeted investigations may generate more granular insights into particular dimensions of ELM integration.

The use of structured prompts, including inspiration cards, emotion cards and regenerative ecology stimuli cards, supported multidisciplinary dialogue and surfaced cross-cutting considerations. At the same time, such scaffolding may have shaped the direction of discussion, foregrounding certain themes while potentially constraining others. Iterative refinement of these tools, or comparison with less-structured ideation formats, would help assess how methodological framing influences emerging imaginaries.

Finally, while concerns regarding the ethical and regulatory aspects of ELMs have been highlighted in the related literature, this study did not systematically examine these dimensions. Future work should integrate inquiry into these dimensions to better understand pathways towards responsible development and long-term integration of ELMs.

Conclusion

ELMs are moving from laboratory innovation towards everyday life integration, bringing not only new technical capabilities but also new societal questions. While much research on ELMs focuses on performance optimisation, this study examined how ELM developers engage with and reflects on the implications of emerging self-healing ELMs before their applications and trajectories become fixed. Our findings through a multidisciplinary co-design workshop frame self-healing as more than functional repair: it is a visible, temporal and relational process. A process that transforms objects, leaves traces and invites interaction. The future concepts revealed recurring orientations around regeneration, co-evolution, environmental embedding and perceptible change. Further discussions of implications showed that concerns about trust, safety, economic logic and ecological responsibility were equally significant as technical considerations. These findings suggest that integrating living behaviour reconfigures how materials are interpreted and evaluated. As ELMs become more autonomous and adaptive, questions of agency, control and meaning become central to their development. Supporting responsible and context-dependent ELM innovation may therefore require not only advances in biofabrication, but also sustained engagement with design and collective reflection.

Data availability statement. All raw data from the workshop is available upon request. The context cards, inspiration cards, brainstorm cards, emotion cards and brainstorming canvas are available here: https://www.regenerativematerialecologies.com/self-healing-tools. The X_Heal Toolkit is available here: https://www.regenerativematerialecologies.com/xheal-toolkit.

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Ethical standards. This study was conducted in accordance with institutional ethical guidelines. All participants provided informed consent prior to participation.

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Appendix

Appendix A. Examples of workshop probes

This appendix provides representative examples of the workshop probes used during the co-design session. The probes were designed to structure ideation, stimulate cross-domain associations and support systematic articulation of self-healing behaviours. The full set of prompts is provided in Appendix B.

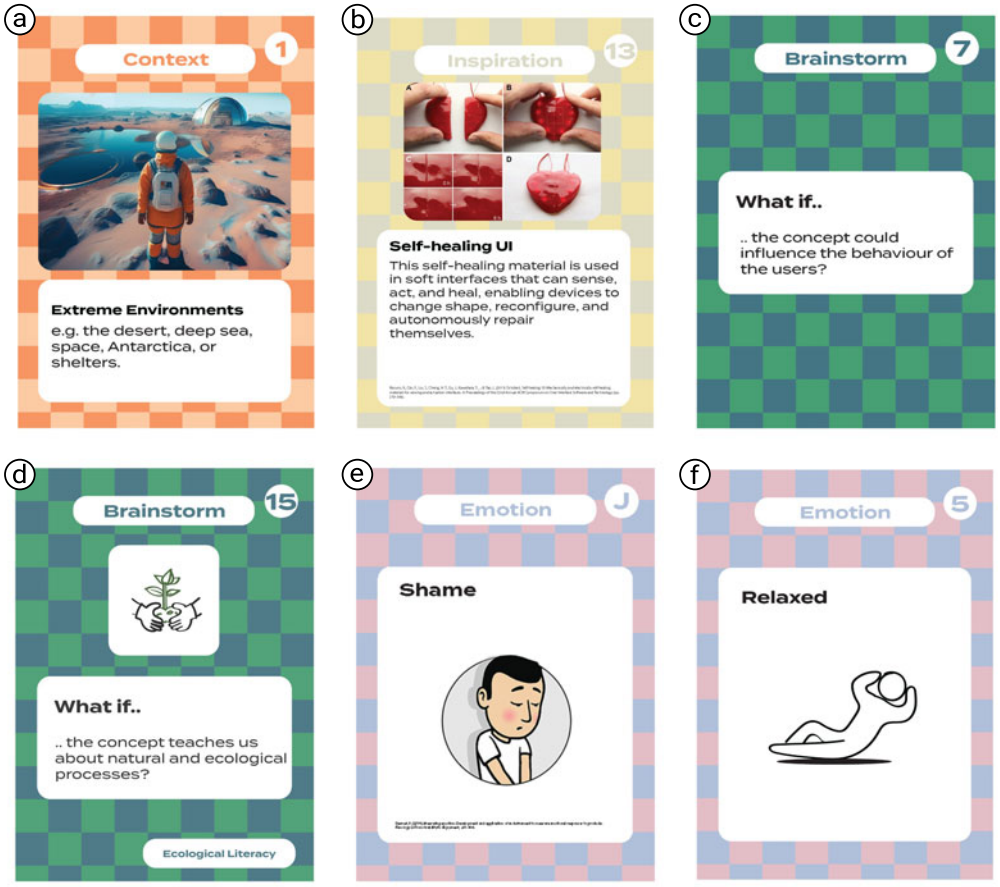


Figure A1. Representative examples of the workshop probes. From left to right and top to bottom: (a) context card, (b) inspiration card (material science), (c) brainstorm card (general), (d) brainstorm card (regenerative ecologies), (e) emotion card (Barrett and Russell 2014) and (f) emotion card (Desmet 2018).

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Context card nr.: .....

Round nr.: .....

Inspiration card nr.: .....

Brainstorm card nr.: .....

Space to brainstorm, sketch, write keywords etc.:

Proposal title final concept: .....

Explain final concept in one or two sentences *(optional: add a sketch)**:***

Figure A2. Blank brainstorming canvas used to document card combinations, sketches and evolving concepts during each ideation round.

Appendix B. Full prompt list brainstorm cards

This appendix presents the complete set of "What if?" prompts used during the co-design workshop. The prompts were designed to stimulate divergent thinking and encourage alternative framings of repair, transformation and material behaviour. General prompts were used in Rounds 1–2. In Round 3, prompts informed by the Living Artefacts for Regenerative Ecologies framework (Karana et al. 2023) were introduced to foreground ecological and relational dimensions of self-healing materials.

B1. General prompts (Rounds 1–2)

1. What if. the concept gave the user something unexpected?
2. What if. the concept can be moved to different locations?
3. What if. the concept offers full customisation?
4. What if. the concept could be shared?
5. What if. the concept went from ownership to rentals?
6. What if. the concept helped the user save money?
7. What if. the concept could be influenced the behaviour of the users?
8. What if. the only driver to buy the concept was sustainability?
9. What if. the concept had no limits in cost or technology?

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10. What if. the concept could bring joy?
11. What if. the concept could solve a problem in a unique way?

B2. Regenerative Ecologies Prompts (Round 3)

12. What if. the concept could fit in natural cycles? (*Cyclical Material and Energy Systems*)
13. What if. the concept fosters different life forms? (*Biodiversity*)
14. What if. the concept creates awareness and collaboration with other organisms? (*More-than-human Sensibilities*)
15. What if. the concept teaches us about natural and ecological processes? (*Ecological Literacy*)
16. What if. the concept inspire

Appendix C. Thematic Analysis Overview

This appendix provides an overview of the final thematic framework derived from the analysis of workshop materials and group discussion transcripts. Themes were iteratively developed through investigator triangulation and clustered around recurring patterns in future imaginaries, motivations and integration concerns.

Main Theme	Sub-theme	Sub-topic	Meaning	Quote
Ecological Aspects	Uncertainty	Emissions and Material Release	Uncertainty about emissions and material release into ecosystems.	*"Emissions affect coral reefs, but I'm not sure how ammonia would affect things around it."*
				"We also have to consider if you drop huge piles of calcium and calcite in nature, that also impacts the environment. It's a natural mineral, but it does change the environment."
		Context Dependent	The impact depends on where they are deployed.	*"But with the urea discussion and with the ammonia, for children they might put their hands in their mouth, cause that is what they do. That is something we should consider."*
				"This is particularly relevant for a concept that imply, you know, to be used in a natural context or in the environment."
		Environment Exposure	Environmental exposure changes material.	*"Feel like it's aged, or it's been affected by the environment and it's changed."*
	Diverse Narratives	Natural Replacement	Sustainability framed as natural vs synthetic rather than biodegradability. Environmental benefit framed comparatively, alternative to fossil plastics.	*"And I'm thinking not about biodegradability, but natural versus synthetic."*
				"The calcite formation is a natural process. While fossil-based plastics are anthropogenic."
				"It was important that this is an alternative to the use of plastic."
		Lifecycle Extension	Self-healing framed as extending product lifetime.	*"The remolding and the reshaping, so it keeps them continuing making. It Extend a lifetime. Forever. Forever."*
Social, Economic and Technical Implications	Trust	Safety (value for acceptance)	Safety is a need and parental responsibility.	*"If it's healthy or safe, the parents might accept it."*
				("And as the kids will play with this or use it, so it should be safe.")
		Familiarisation	Small-scale exposure (children) framed as pathway to acceptance.	*"Starting small steps kids getting used to this and it's also like sparking people's curiosity with like an easy example and then also if it's children that get used to these kind of self-healing things maybe it's helping for getting self-healing materials get more accepted."*
		Functionality	Existing technical standards (e.g., strength, toughness, form) may be difficult to meet with self-healing living materials.	*"Maybe even if it fits the requirements that people think, for example, for a helmet, if it's broken, that they still don't trusted even though you fix it."*
				"For many products there might be guidelines on what kind of shape and what kind of strength and toughness they should have. And that could be challenging to meet those requirements. Because maybe the self-healing makes it better, but it doesn't exactly fit requirements, so it's better that you use it."
		Material Agency	Doubts remain after healing, and autonomy and unwanted healing undermine trust.	*"You wake up and your house is full."*
				"I wonder also what happens if it self-heals when I don't want it to self-heal."
	Experiental Value	Aesthetic Appeal	Aesthetic outcomes make self-healing desirable and differentiable.	*" I think aesthetics is a really interesting one. (...) So in a way, self-healing can also be thought of as a unique selling point."*
		Aesthatic Adaptation	Self-healing seen as renewal over time (for trends, seasons) framed as value.	*"...if you perceive self-healing as, for example, adaptability in the sense that you can erase something and have it anew. So if you have a pattern, if you apply a sort of pattern and image onto something on a textile, then you can completely renew it and the next season there's a different trend."*
		Interaction	Material changes and is customized based on interaction.	*"I like the idea that people would have a product that, based on their interactions with it and how it interacts when they take it out into the real world, that they can customize it. (...)"*
		Performativity	Expressing individual identity via self-healed material.	*"Especially if it's something that they're going to live with in repair, then it feels like something that you would want to feel like customised. Like I can imagine for a helmet, like if it was a helmet for skateboarders, then those.. Some people, they might do things like intentionally break it and fix it so that they can get lines in it in certain patterns just to show off to people."*
	Techno-Economic Systems	Durability vs Sales Logic	Durable products challenge replacement-based economy logics.	*"What if I'm the investor and everyone buys it? The product and no one ever buys it again"*
				"Very durable business models of companies, car companies that invest also in having good maintenance support and that could also be a business model and then still fit in this ecological."
		Repair as Value Proposition	Self-healing aligns with expensive, long-lasting products.	*"At some point some products are just so expensive and just throwing away and buying another one doesn't work, right? When my car gets scratched, I don't throw away the car."*
				"Expensive things that, or big things that are hard to just get another one, like houses and aeroplanes."
		Service-based / Subscription Models	Business models shift to maintenance and subscriptions.	*"You can have a subscription base here that only heals when you have a subscription."*
		Demand / Necessity	"Good enough" alternatives reduce the motivation to change them.	*"Why would consumers necessarily have like the need to want to buy our product over something that we already know and are familiar with and it doesn't self-heal, but it does the job."*
		High Material Costs	Costs of living materials are possibly quite high.	*"There's also the element of the material that we would create would be quite expensive. It's bacterial cellulose and the living element to it."*
Development Trajectories	Biological Computers		Biological signaling imagined as interaction infrastructure.	*"...If we achieve a point where living organisms and microorganisms are like a part of everything we interact with, any technology, then in a way maybe there would be also the interaction between the living organisms in the same sense that we have like wireless charging or something that there would be quorum sensing molecules coming out of my table onto my device to show that it's charging."*
	Programmability		Living materials imagined as updatable functional systems.	*"This material reminds me a little bit of digital systems, right? We get updates, regular updates on systems. So there's a programmable functionality."*
			Form/function changes imagined through interface-like purchases.	*"...Actually when I put my telephone on it, it will start charging my table because the new functionality had been activated. New updates come to the material."*
				"...if you want like the Bauhaus chair, and you want your chair to morph into a Bauhaus chair, well then you have to buy a thing that would enable the genetic composition of your organs to morph into that particular shape, or your clothing, or whatever. So it would be like a digital bio-interface."
	Co-evolution with Users and Environments	Personalisation through Growth	Products grow with users and reflect identity; encourages care.	*"So that's something that I would like to see, at least, that you grow your own products to be custom-made for you, but also reflecting your personality,"*
				"if you have a living ... furniture that sort of evolves with you. I think you can nicely address that we take more care of our products as well, which then obviously leads to environmental impact."
		Environmental Adaptation	Materials imagined to adapt/mutate with climate/environment changes.	*"for the living material is like it has agency it can evolve and mutate according to their environmental change so it adapts to a new environment so if you reflect on the climate change that we are facing with our products may have really different appearance for 100 years later, because the temperature of the earth may change, the moisture change, and our product also mutate and evolve according to this climate change."*
		Relational Entities	Materials and organisms imagined as "companion species".	*"...also maybe you are creating new species, companion species."*
				"I think you can nicely address that we take more care of our products as well, which then obviously leads to environmental impact."

Figure C1. Thematic Analysis framework with main themes, subthemes, subtopics and illustrative quotes.

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