Manufacturing Immortality

Self-Healing Materials in the Circular Economy

Case Study: Consumer Electronics

EPSRC
Pioneering research and skills
Funded Collaboration

University of Bristol · University of Exeter · Heriot-Watt University · Lancaster University · The University of Manchester · Northumbria University Newcastle · Sheffield Hallam University

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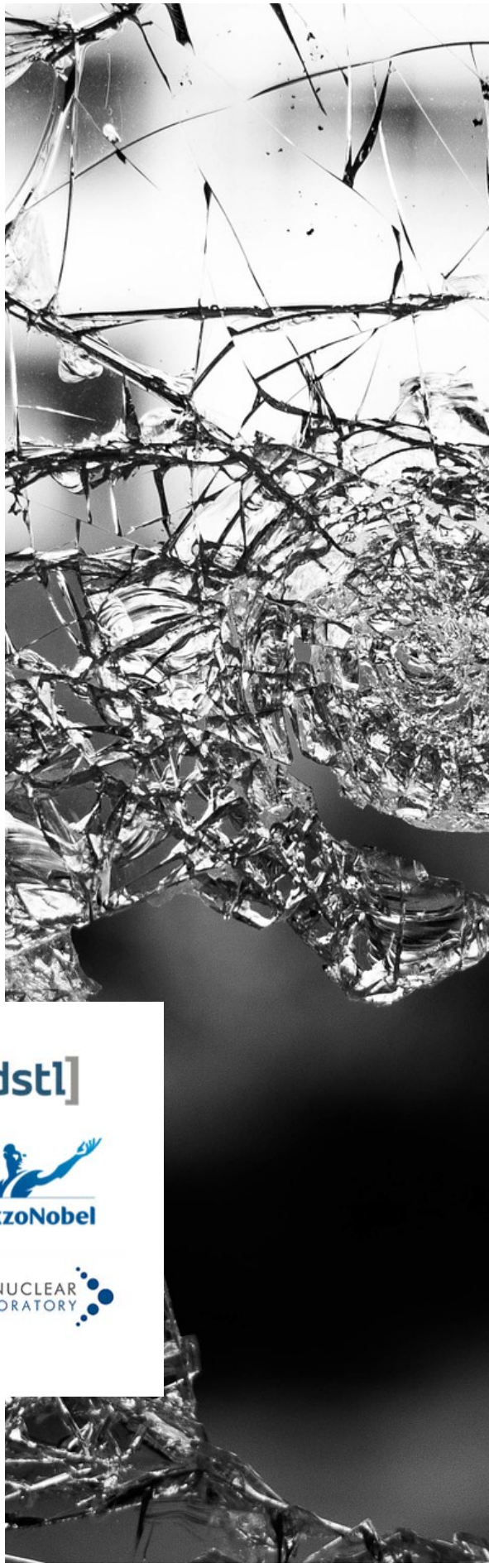
Introducing the Manufacturing Immortality Project



Manufacturing Immortality was a three-year EPSRC funded research project investigating self-healing materials (2018-2021).

The project was a collaboration between seven universities. Each university brought a different specialist expertise to the research to create an interdisciplinary research team: chemists, biologists, scientists, engineers and designers all working together to explore the feasibility of developing, manufacturing and designing with self-healing materials.

- University of Bristol: developing bio-based self-healing mechanisms for materials
- University of Exeter: understanding how self-healing fits in a Circular Economy
- Heriot-Watt University: using AI and machine learning to make research more effective
- Lancaster University: exploring the use of self-healing membranes on hydrogen fuel cells
- University of Manchester: exploring the manufacturing science of self-healing materials
- Northumbria University Newcastle: developing self-healing polymers
- Sheffield Hallam University: developing radiation resistant glass

The research team worked closely with industry partners:

AFC Energy · SIEMENS · The Data Lab · dstl · Ellen MacArthur Foundation · ITM Power · AkzoNobel · Overlander Batteries · Zentraxa · CENSIS · National Nuclear Laboratory

This case study illustrates the role self-healing materials can play as we move to a Circular Economy.

Code Red for Humanity

A Planet in Crisis

Since the Industrial Revolution, human activity has had a devastating impact on the natural world undermining the natural resources upon which we rely, such as the food we eat, the water we drink, the air we breathe and the materials and resources we need to make the products we buy.

'We are eroding the very foundations of our economies, livelihoods, food security, health and quality of life worldwide.'

Sir Robert Watson, Chair of the IPBES [i].

Climate Change

Due to human activity, climate change is widespread, rapid and intensifying, with some trends (such as sea level rise) now irreversible. Extreme weather events, such as heatwaves, floods, tropical cyclones, droughts and wildfires are becoming more frequent and intens [ii].

'It's code red for humanity. The alarm bells are deafening, and the evidence is irrefutable.'

António Guterres, UN Secretary General [iii].

Biodiversity Loss

Human activity, such as intensive farming and urbanisation, has led to catastrophic biodiversity loss with a million species at risk of extinction globally [iv].

'The damage we are inflicting on species and ecosystems is so extensive and profound that scientists now believe we are witnessing Earth's sixth mass extinction event – the last one marked the end of the dinosaurs.'

Sir David Attenborough [v].

Resource Scarcity and Security

As the global economy grows, the supply of non-renewable resources (such as metals and minerals) may struggle to keep pace with demand threatening economic stability.

'Dependence on scarce natural resources exposes a company's tangible and intangible value to serious risks.'

Accenture [vi].

We need to change

‘The world will not evolve past its current state of crisis by using the same thinking that created the situation.’

Albert Einstein [vii].

We need ‘deep-rooted shifts in values, norms, consumer culture and underlying worldviews.’

On The Brink, IPCC Emissions Gap Report, 2019 [viii].

The Circular Economy

'The IPCC tells us we have a short window to act to avoid catastrophic climate change. To do so we must move from our linear, polluting and wasteful economy to a Circular Economy, and fast.'

Sean Kidney Chief Executive Officer, Climate Bonds Initiative [ix].

Business is Changing

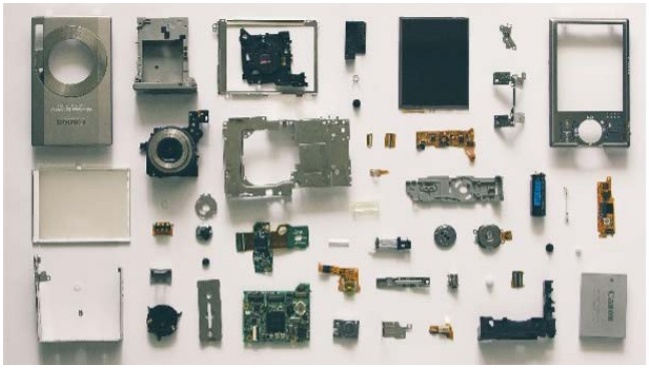
Policymakers, investors and industry are moving away from the linear, take-make-waste economic model where value is created through ownership of a product. Instead, they are embracing the Circular Economy which aims to design out waste and pollution, keep products and materials in use, and regenerate natural systems [x, xi, xii, xiii, xiv].

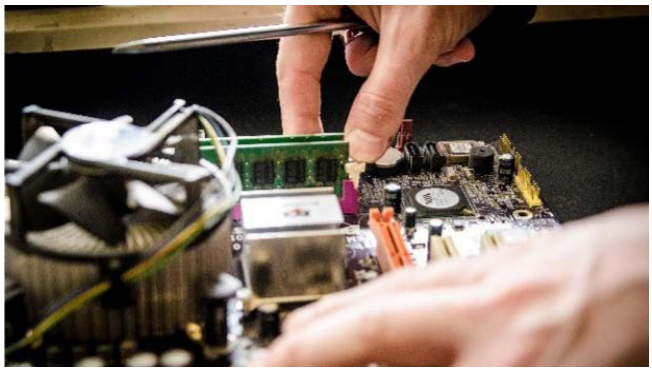
'One day in the future, in a Circular Economy we won't even have the concept of waste! This is how we can truly steward the resources of our planet, our economy, and humanity.'

Erika Karp Founder and Chief Executive Officer, Cornerstone Capital Group [xv].

Circular Design

Design strategies in a Circular Economy move away from a 'cradle to grave' approach whereby products are used, discarded and then often incinerated or dumped in landfill. Instead, a 'cradle to cradle' or Circular Design ethos is employed, whereby the end of life of the product is considered at the design stage, so that materials, components and products can be kept in use for longer and easily reused, repaired, remanufactured or disassembled for recycle.





'A Circular Economy is key to building an economic system that is viable in the long run, in which value is created and maintained, rather than extracted and wasted.'

Keith Tuffley Managing Director & Vice Chairman, and Global Co-Head of Sustainability & Corporate Transitions, Citi [xvi].

Circular Business Models

Circular business models aim to reduce the use of resources by redefining how we deliver value and function of products to consumers. For example, rather than buying products, consumers would rent or access services. This incentivises companies to design for durability and repairability, not obsolescence. It's a virtuous circle: circular business models encourage circular design.

'Tomorrow's economy will only be resilient if a new paradigm is promoted, that of the Circular Economy, based on use rather than possession and on more effective and sustainable management of resources.'

Groupe Renault [xvii].

Restorative and Regenerative

In a Circular Economy, regenerative practices are embedded within agriculture and industry. Regenerative farming closes the carbon loop by extracting carbon dioxide from the atmosphere and locking it back into the soil or plant material, such as hedges or trees. On regenerative farms, biodiversity is actively restored.

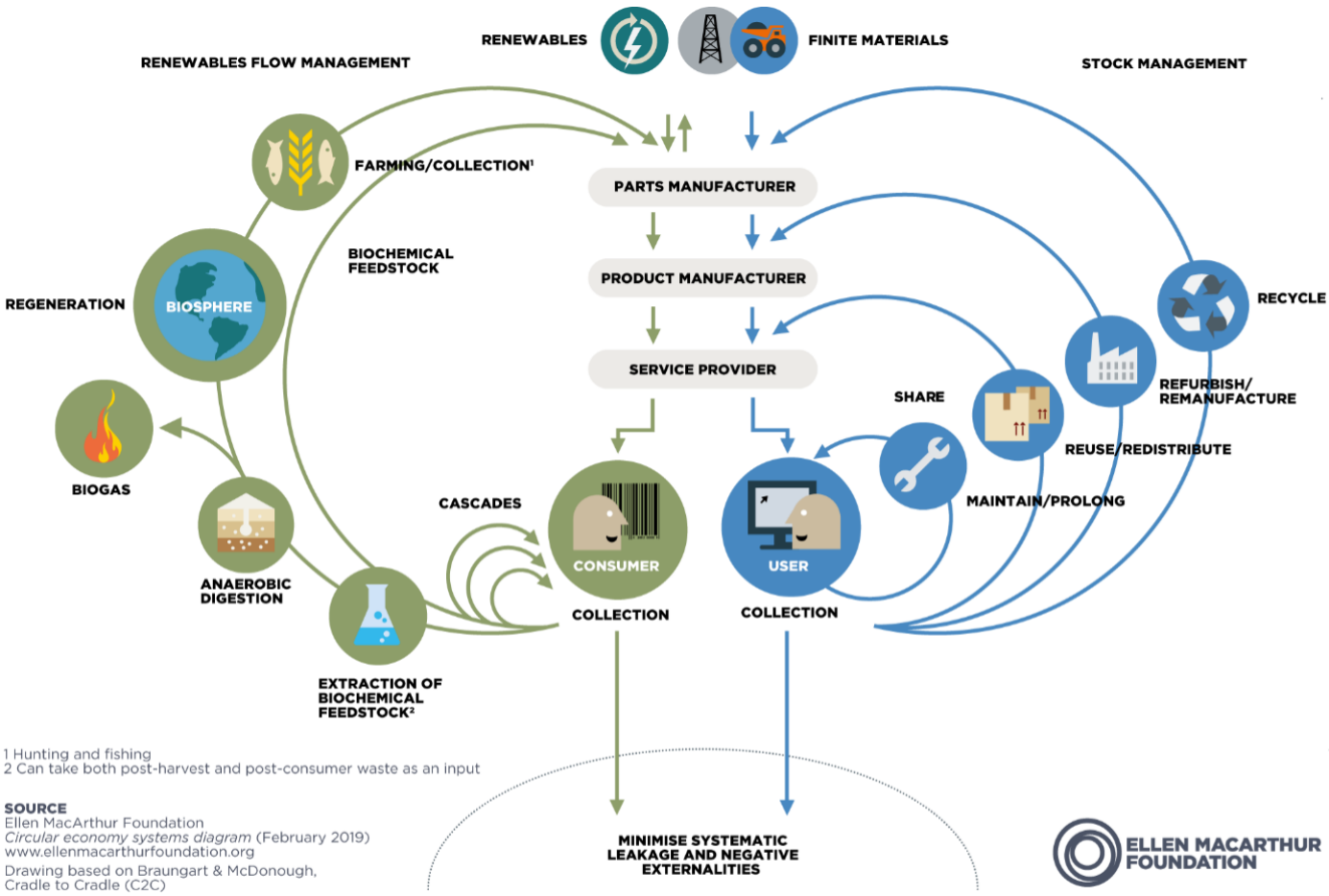
These strategies can be applied to industry. Cradle to Cradle pioneers, Braungart and McDonough worked with a textile manufacturer to produce a fabric whose ingredients not only did no harm but had positive qualities. When the material went into production and regulators came to check the factory's effluent (the water coming out of the factory), they could not identify any pollutants, not even chemicals they knew were in the water when it came into the factory: the water coming out of the factory was as clean as – or even cleaner than – the water going in [xviii].

'Buildings could become an active part of local ecosystems, harvesting carbon dioxide from the environment to heal themselves. The walls of buildings could act as bioreactors, using inputs such as light, water, heat, algae, bacteria, nutrients and gases to generate a range of products such as purified water, power, oxygen, recoverable biomass and heat.'

The Royal Society [xix].

An Economy for the 21st Century

The Circular Economy is an economic system fit for the 21st Century.
It enables us to live within planetary boundaries, whilst maintaining living standards.



A Circular Economy offers companies the opportunity to create value whilst at the same time providing social and environmental benefits.

'The Circular Economy redefines the approach to value creation. Companies that shift towards a circular model can increase their medium- to long-term competitiveness, becoming more appealing to financial institutions in terms of funding and financial support, while creating a positive impact within local communities.'

Carlo Messina Chief Executive Officer, Intesa Sanpaolo [xx].

'The Circular Economy offers a crucial combination of economic opportunity and enhanced environmental outcomes.'

Audrey Choi Chief Sustainability Officer and Chief Marketing Officer, Morgan Stanley [xxi].

Self-Healing Materials in a Circular Economy

Self-Healing Materials and Product Life Extension

The Manufacturing Immortality project focused not only on developing new compositions of self-healing materials but also investigating their application and sustainability implications, so we could contribute both towards this technological transition and advance their use within industry.

Moreover, we believe these materials could play a crucial role in a transition to a Circular Economy through extending a product's lifespan (a fundamental principle of the Circular Economy [xxii]), as well as improving safety and reliability [xxiii].

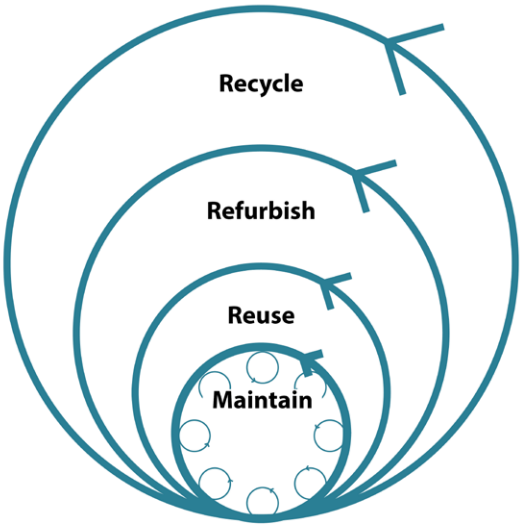
Self-healing materials and coatings can contribute to product life extension in the following ways:

- By helping to maintain aesthetic resilience, so a product can retain its value. Consumer appliance manufactures and designers were consulted and agreed that self-healing surfaces would be highly beneficial for electronics, fridges, ovens and cookers, as 'consumers are looking for durable surfaces that look premium and are easy to clean' [xxiv].
- By helping to restore functionality. Glass, polymers, concrete or asphalt with small cracks or defects could repair themselves. There are many applications for these types of self-healing materials, such as consumer electronics, printed circuit boards, buildings, roads, pavements and fuel cells. Some self-healing products are already commercially available, such as, car and bicycle tyres [xxv].

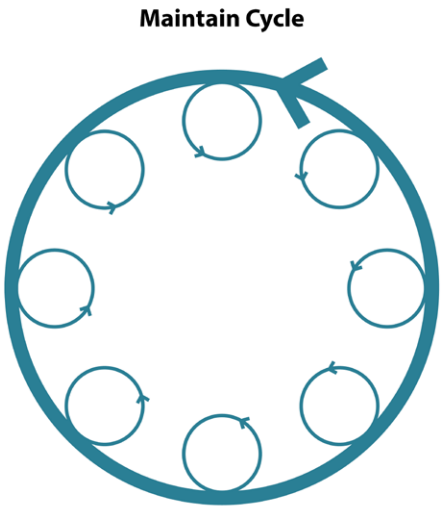
Some applications could improve **both aesthetics** and **functionality**, for example, self-healing coatings on metal infrastructure like bridges, could help to protect the metal and reduce corrosion. Given the worldwide cost of corrosion has been estimated to be nearly $300 billion per year, this could be an important application [xxvi].

Lastly, self-healing materials also may be particularly useful in areas where it is difficult and expensive to repair products, such as those deployed within space, at sea or within the human body and there may be applications within the renewable energy sector, for example, for offshore wind turbines.

Framework for Self-Healing in a Circular Economy [xxvii]



Circular Economy System



Self-healing materials in a Circular Economy

How does self-healing work?

Self-healing is typically described as either: **intrinsic** – whereby the material itself may have innate properties that enable self-healing, with molecular bonds breaking and then reforming often requiring an external trigger to self-heal, such as heat, light or pressure. Or **extrinsic** – whereby a healing agent may be embedded within the material via microcapsules or vascular networks.

Glass

Our researchers at **Sheffield-Hallam University** have developed a low-cost radiation resistant glass through modifying a commercially available soda-lime-silica glass to improve its structural integrity and reduce discolouration when exposed to radiation. Our team from Northumbria University are exploring coating the glass with a self-healing material to improve scratch resistance and further extend its product life.

Key applications for this glass are in environments where extreme radiation resistance is crucial, such as, within the space and nuclear industries. The glass could also be used within the energy sector, for example, in solar panels, or in everyday products, such as, glasses, cameras or mobile phone screens.

Polymers

Usually if the bonds between polymer chains are ruptured, they are permanently damaged and the product may need to be discarded. Our researchers from **Northumbria University** have developed an **intrinsically self-healing polyurethane**: the intermolecular bonds can be reattached, a bit like Velcro. The polymer can be sliced in two and then pressed back together to trigger self-healing within a few seconds. This healing process can occur many times. Once healed, the polymer's functionality and tensile strength is restored, extending the product's life.

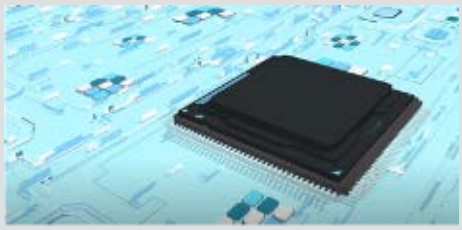
Our researchers are developing this self-healing material so that it can be moulded into different components and products. It could have many applications and would be particularly useful in areas where products are inaccessible or costly to repair.

Watch our animations on YouTube to find out more:

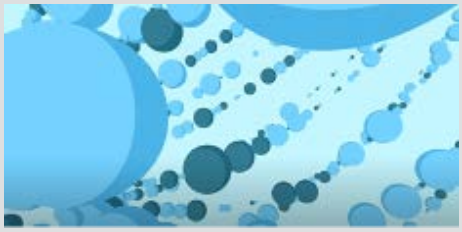
Understanding the sustainability benefits and uses for self-healing materials and products

Low-cost radiation resistant glass

Using machine learning for self-healing materials



Intrinsically self-healing thermoplastic poly-urethane



Self-Healing and the Circular Economy: Consumer and Industry Perspectives

As part of the Manufacturing Immortality research project, we gathered insights from consumers and industry on how self-healing products could fit within a Circular Economy, exploring both the perceived benefits as well as concerns and risks [xxviii].

Industry Perspectives

What are the benefits of self-healing materials in a Circular Economy?

Our research identified three key areas where industry experts felt self-healing materials would help them move towards a Circular Economy.

1. **Extending product life span**. Industry participants explained that 'minor defects like cracks on glass' or 'scratches due to mechanical damage' often result in premature disposal. Participants felt that if self-healing glasses or coatings were to be integrated to particular components or surfaces, 'this could definitely do the job of lowering waste rates'.

2. **Increasing ease of disassembly and reassembly**. One participant, who refurbishes consumer electronics, explained that due to methods used in the assembly of screens, separating the different layers for repair often results in further damage and value loss. Self-healing polymers, adhesives or hydrogels that could be easily cut and re-bonded could help alleviate this issue and facilitate modular design which enables repair.

3. **Transition to circular business models**. Participants felt that self-healing coatings could enable a transition to such circular business models, such as product as a service, by keeping products looking and functioning in premium condition for longer.

What are the concerns?

1. **Persistence**. Several participants observed that if materials have the ability to either re-bond or release 'healing agents' autonomously with no deliberate human action, this might present issues at end of life, for example, exacerbating problems like persistence of plastic litter in our oceans [xxix].

2. **Monstrous Hybrids**. A founding principle of the Circular Economy is the separation of 'technical' and 'biological' nutrients to ensure these can be easily recycled and avoid 'Frankenstein products' or 'monstrous hybrids' [xxx]. Participants recommended that future researchers exploring bio-hybrid self-healing materials should consider strategies that allow biological components to be easily and safely removed or deactivated, for example, in the case of concrete or polymers with biological components like bacteria.

3. **Liability**. Participants spoke of the need for a greater understanding of the 'safety and liability [implications] of keeping a healed product in service'.

4. **Limitations**. Self-healing has shown to be effective at repairing small scale damages such as micro cracks and scratches but the healing of larger damages is not yet possible in real world situations, as self-healing bulk materials have only been lab tested so far.

Consumer Perspectives

We also surveyed 140 consumers from around the world to gain a greater understanding of their attitudes to the Circular Economy and self-healing products.

Over 95%

Over 95% of respondents said that the environmental credentials of a product affected their purchasing decision: over 50% said it did most or all of the time. Others did not seem to find a consumer culture problematic:

'New replacement products are cheap.'

Over 84%

Over 84% of consumers we surveyed were interested in self-healing products, although some expressed reservations:

'Just not sure what self-healing means and whether this is more tech to add to the general tech noise of the world'.

Almost 90%

Almost 90% said they would be willing to pay more for a self-healing product. The majority of people were prepared to pay 10-30% more for a self-healing product.

Consumers demonstrated a mixed response to circular business models. 47% said they would be somewhat or extremely interested in renting, rather than owning products, such as a phone, laptop or furniture. 41% said they were not interested or there was '*absolutely no way*' they would consider renting such items. This demonstrates that whilst consumers seem open to products with environmental credentials, they seem less open to circular business models, perhaps reflecting that this move represents a larger cultural shift.

Consumers expressed a range of views about the role of self-healing materials in rental models. Some consumers were positive about the concept as it would enable products to look better for longer:

'The wear from previous renters would be less noticeable and it should feel more new.'

'I would think it [the product] would be in a better condition because it heals itself regularly.'

One participant liked the concept of renting self-healing products because it could enable greater continuity:

'I hate changing products (new phone, new laptop etc), so if renting a self-healing one meant extending the life of the product I had (especially significantly), I would be in!'

A key factor in the value of self-healing materials within rental models was the question of who was liable for damage:

'If you are renting a product, I assume it is the service provider's responsibility to fix/ refurbish the product so it shouldn't make a difference to the user if it was self-healing? I think a self-healing product is much more attractive when it is owned by the consumer.'

'If I was renting a regular product and it got damaged, I would assume that I could get it replaced as part of the contract so I wouldn't see the benefit of it being self-healing.'

These responses suggest that by enabling the product to maintain its appearance and functionality, self-healing materials are perceived as more beneficial to the business, rather than the consumer.

The Circular Economy, Self-Healing and Consumer Electronics

Batteries, Materials and Resource Sovereignty

As we transition to a clean, green economy, the demand for the rare metals (such as, cobalt and lithium) needed to make rechargeable batteries will grow.

Batteries will not just be used in consumer electronics but in electric vehicles and to store energy from renewable and fluctuating sources (such as wind and solar). However, the extraction and production of both these rare metals is concentrated in regions of political instability, so geopolitical tensions and nationalistic policies pose a risk of supply chain disruption [xxxi, xxxii]. For example, considering the uncertainty of the political situation in countries like Bolivia, Chile, Argentina, the supply the supply of lithium which is rapidly growing demand may not fully reliable [xxxiii].

'Companies face a rapidly increasing challenge, and opportunity, to grow their businesses and create value amidst volatile and scarce supply of natural resources.'

Accenture [xxxiv].

Circular Economy strategies and the use of self-healing materials keep resources, i.e materials, components and products cycling in the system for longer, offering companies resource sovereignty which can improve economic resilience, as well as reduce environmental impacts. The circular paradigm offers resource independence.' Ellen MacArthur Foundation [xxxv]. A strategy that some organisations are actively pursuing.

'At Nike, we believe that in order to continue to thrive we cannot wait to see what uncertainty brings; instead we build our business by decoupling our growth from resources that are becoming increasingly scarce. This isn't our sustainability strategy, it's integral to our business strategy.'

Hannah Jones, Vice-President of Sustainable Business and Innovation at Nike [xxxvi].

Maintaining functionality in complex products

When electronic components such as wiring or batteries fail in complex or sealed products this results in either the product being discarded or incurring costly repairs. Self-healing conductive materials is a promising area of research attempting to mitigate this issue and has been suggested for self-healing circuits and extending the lifetime capacity of batteries. For example, silicon (as opposed to graphite) anodes are preferable as they can hold many times more energy, and therefore, dramatically increase the usage time and energy efficiency. However, silicon anodes are prone to expansion which leads to cracking and degradation [xxxvii]. Self-healing compositions could solve this issue: cracks in silicon anodes can be self-repaired so that their efficiency is restored to between 95 and 100% [xxxviii].

Self-healing conductive polymers are also being suggested for self-healing circuits and wiring to prevent loss of function. This is in particular is being suggested as particularly significant for soft robotics and wearable electronics [xxxix, xl].

Aesthetic Resilience, Refurbishment and Reuse

Self-healing materials can support with moving to a Product Life Extension model within consumer electronics. An example we studied within the Manufacturing Immortality Project was the use of self-healing coatings to ensure the aesthetic resilience of refurbished TV and broadband boxes.

These products can have a lifespan of up to 8 years during which time they may be installed in up to 5 different households [xli]. The internal electronics can remain intact (and be tested and reused) but if the outer casings are scratched or damaged, they often need to be replaced and thrown away.

These covers have all been replaced, even though only have minor cosmetic damage.

One participant in our study (who is involved in the repair and refurbishment of set-top boxes) explained that this creates significant environmental and economic costs for both the manufacturer and refurbisher. A self-healing coating on the casings could address this issue through allowing them to maintain a 'good-as-new' condition as they pass between different users.

Refurbishers felt that triggered self-healing would be preferred over autonomous self-healing, as this would assist the refurbisher in being aware of what damage had occurred and allowing them to provide the service of repair to their customers.

However, the purpose of this model would need to be clearly communicated to consumers, as some were sceptical of the use of self-healing materials if this did not prevent interruption of the use of the product and products still needed to be sent away to be for self-healing to be triggered.

'I don't like the bureaucracy and the time it takes to get something fixed by another person'

'Sending a product away to be 'healed' disrupts your use of it, and is literally how all these products already work. If a product can't self-heal to avoid disruption of functionality there is no point for the consumer.'

Other consumers we spoke to were clearly motivated by the environmental impact of the products they bought which suggests that this model may work as long as the rationale and sustainability benefits are clearly communicated.

Alternatively, a self-healing coating could be deployed in conjunction with a mechanism that signalled to the refurbisher when self-healing had taken place. This might be more appealing to customers as it would reduce waste (and therefore, address sustainability concerns), whilst at the same time not interrupting use of the product.

Smart Phones and Headphones

Fairphone: Modular Design

'We are going against the make-use-dispose trend, by making modular smart phones that are durable and easy to repair.'

Fairphone[xlii].

Fairphone is a globally renowned social enterprise which is pioneering circular design within consumer electronics. Their smartphones consist of seven modules (such as, the screen, battery and camera). If any of these modules become damaged, they can be taken out, repaired or replaced.

This modular design facilitates hardware and software updates, addressing an industry-wide problem of premature product obsolescence which was highlighted within our research:

'technological products are out dated by time, even if they are not broken'.

For example, when an upgrade for the camera becomes available, it can easily be replaced, rather than the entire phone. Fairphone are also working to support software upgrades for five years – well beyond the industry standard.

Fairphone are aiming to move to a circular business model by offering the 'Fairphone-as-a-Service' (FaaS) and have written a **detailed case study** of how this could work in practice. This model enables manufacturers to create value across the entire lifecycle of the product, rather than solely at point of sale, as they retain ownership of the product. Modular products are ideally suited to this model as they can easily be repaired and so the product life can be extended.

'The modular nature of the Fairphone 2 is a unique strength for the financial viability of the FaaS proposition as circular value creation can be structured around the individual characteristics of modules, rather than on the aggregate performance of the whole device. Furthermore, the ability to target individual modules can result in material savings and have positive environmental impacts.' [xliii]

Self-Healing Smart Phones

Offering 'Fairphone-as-a-Service' would further incentivise designing durable, easy-to-repair, modular products. Self-healing materials would enable this and could have many applications within smart phones: screens, casings, batteries and circuit boards. Self-healing phone screens have already been patented by Motorola [xliv].

Our research suggested that self-healing materials could facilitate modular design by through the use of self-healing seals around each component which would enable easy disassembly and reassembly.

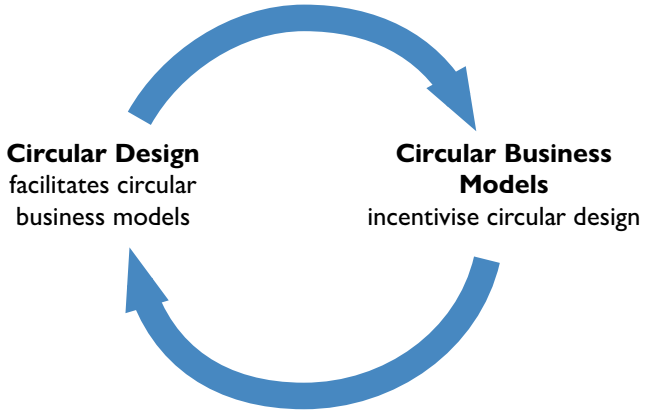
Consumers we spoke to emphasised the appeal of self-healing smart phones and laptops. One reason cited was that phones and laptops contain personal data (documents, emails and photos). Changing devices is inconvenient 'because it has my stuff in it!'.

Gerrard Street: Headphones as a Service

Gerrard Street already use a 'product as a service' circular business model, offering their premium quality, modular headphones on a subscription basis. This means customers are guaranteed free repairs for life. In addition, customers can return the headphones for an upgrade or complete replacement.

Like Fairphone, Gerrard Street have designed their headphones using circular principles. The modular design allows 85% of components to be reused. Products use durable, standardised designs, meaning fewer virgin materials are used to create new headphones. The products are easy to disassemble and repair, and no glue is used making them. If a part fails, customers can simply order a new one, thus extending the lifetime of the headphones[xlv].

Circular principles create a virtuous circle with circular design making circular business models easier to implement and circular business models incentivising circular design.



Consumer benefits:

- guaranteed a high-quality product
- no initial costly upfront payment, instead a small monthly subscription rate

Business benefits:

- increased revenue by maximising the use cycles for every pair of headphones
- more reliable and predictable material supply chain and revenue stream
- closer relationship with customers
- small monthly fee also allows greater market access i.e. customers who would not usually be able to afford to pay for premium headphones

Where do self-healing materials fit?

Self-healing materials make perfect sense within this model because manufacturers are no longer designing for obsolescence, instead they're designing for longevity. With a subscription or 'product as a service' business model, businesses want their products to last as long as possible, and consumers expect products to look good and last longer. A number of respondents to our consumer survey highlighted the appeal of self-healing headphones.

Case Study:
Self-Healing Smartwatches

Electronic wearables is a growth industry expected to reach €77 Billion by 2022 [xlvi]. Fitness bands and smart watches have shown high growth in the past five years (compared with laptops, smartphones and tablets). Ownership remains comparatively small: 22% for wearables compared with 88% for a smartphone (based on 2019 survey of the Belgian population). This suggests there is room for continued high growth in the market.

Traditional electronics are made from materials that are intrinsically rigid and brittle with limited capacity to bend and stretch [xlvii]. Because of this, they are not ideally suited to use within wearables devices (particularly in sports or other contexts): as the wearer moves, the device is likely to suffer strains which may lead to damage.

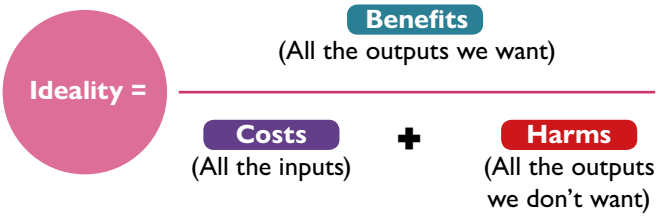
The use of soft electronics, particularly with a self-healing capacity, offers a range of advantages [xlviii]:

- increased durability
- reduced waste
- improved performance
- product life extension
- improved user comfort

Measuring Costs and Benefits

As part of the Manufacturing Immortality project, we developed a framework to measure the costs and benefits of self-healing products in a Circular Economy [xlix]. We built on existing models and metrics (such as, the Life Cycle Assessment (LCA) [l], the Material Circularity Indicator (MCI) [li], the Durability Index [lii], Cost-Benefit Analysis [liii]) and in particular, drew heavily on the TRIZ (Theory of Inventive Problem Solving) Ideality framework [liv] (see Figure 1):

Figure 1. TRIZ Ideality Equation [lv]

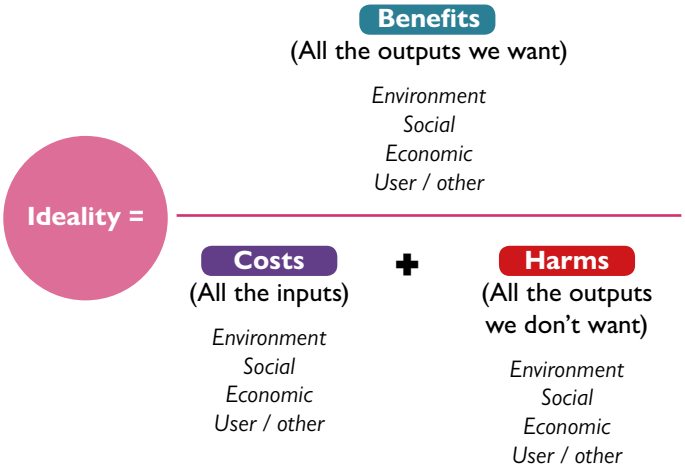


The advantage of this model is that it explicitly articulates the harm that a product or scenario can cause. This forces the producer / user to confront harms, rather than viewing them as 'externalities' for which they have no responsibility. Models or systems which lack an explicit articulation of harm can facilitate a 'race to the bottom' in terms of both environmental and humanitarian standards: industry can be incentivised to cause harm, whilst others are left to pay the price. Based on the 'polluter pays' principle, the implementation of extended producer responsibility (EPR) policies in relation to e-waste seek to address this [lvi].

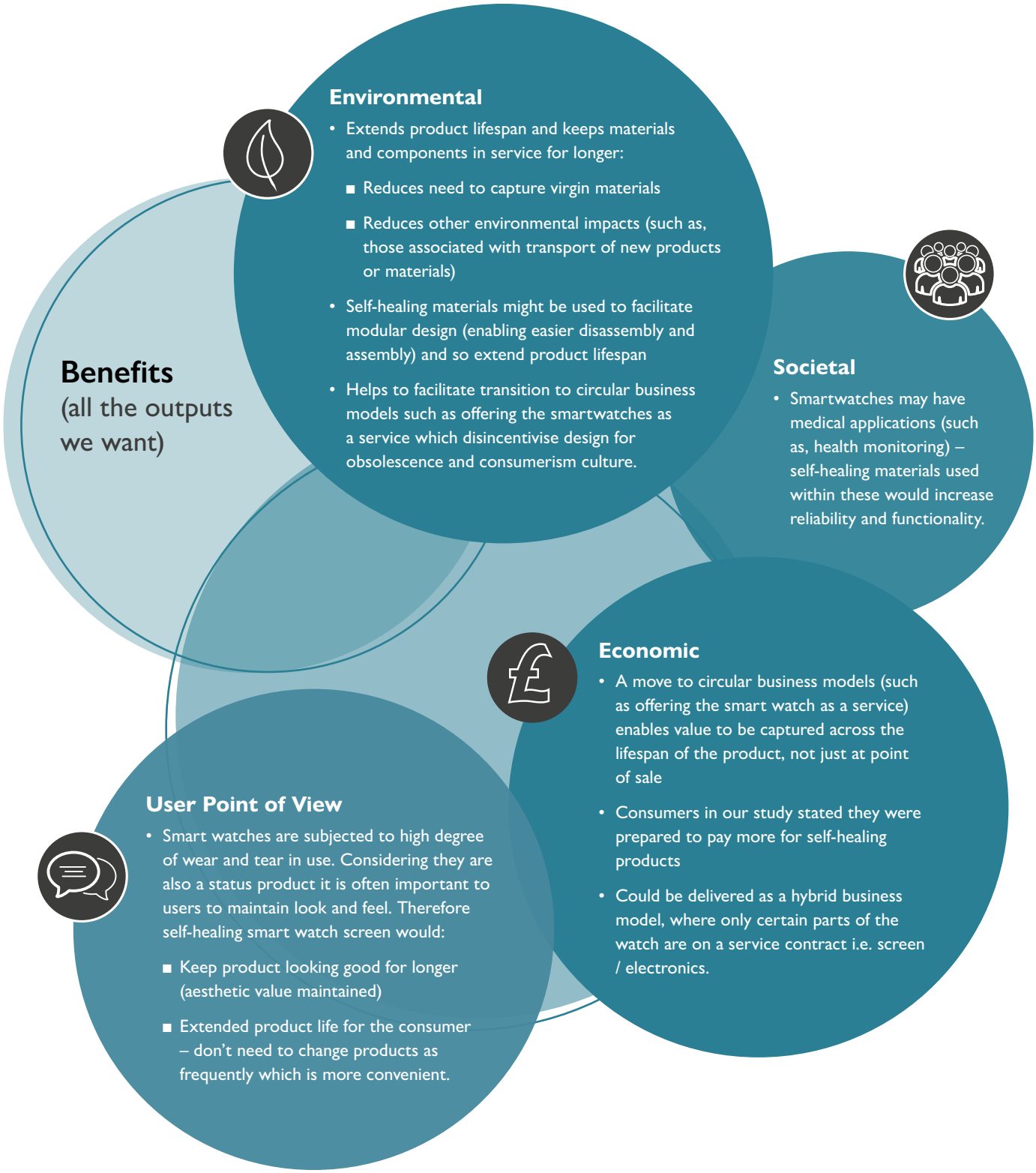
Our model combines the Ideality Framework with a triple bottom line (social, environmental and economic impacts) (see Figure 2). It has potential to integrate both quantitative and qualitative measures. For example, a quantitative metric may be used to measure the extent of self-healing or 'healing efficiency' (a material or product's functionality compared with the original) and how this may be impacted across a product's lifecycle including multiple damage and healing events [lvii]. Qualitative measures may be important to assess consumer attitudes and more value-based perspectives.

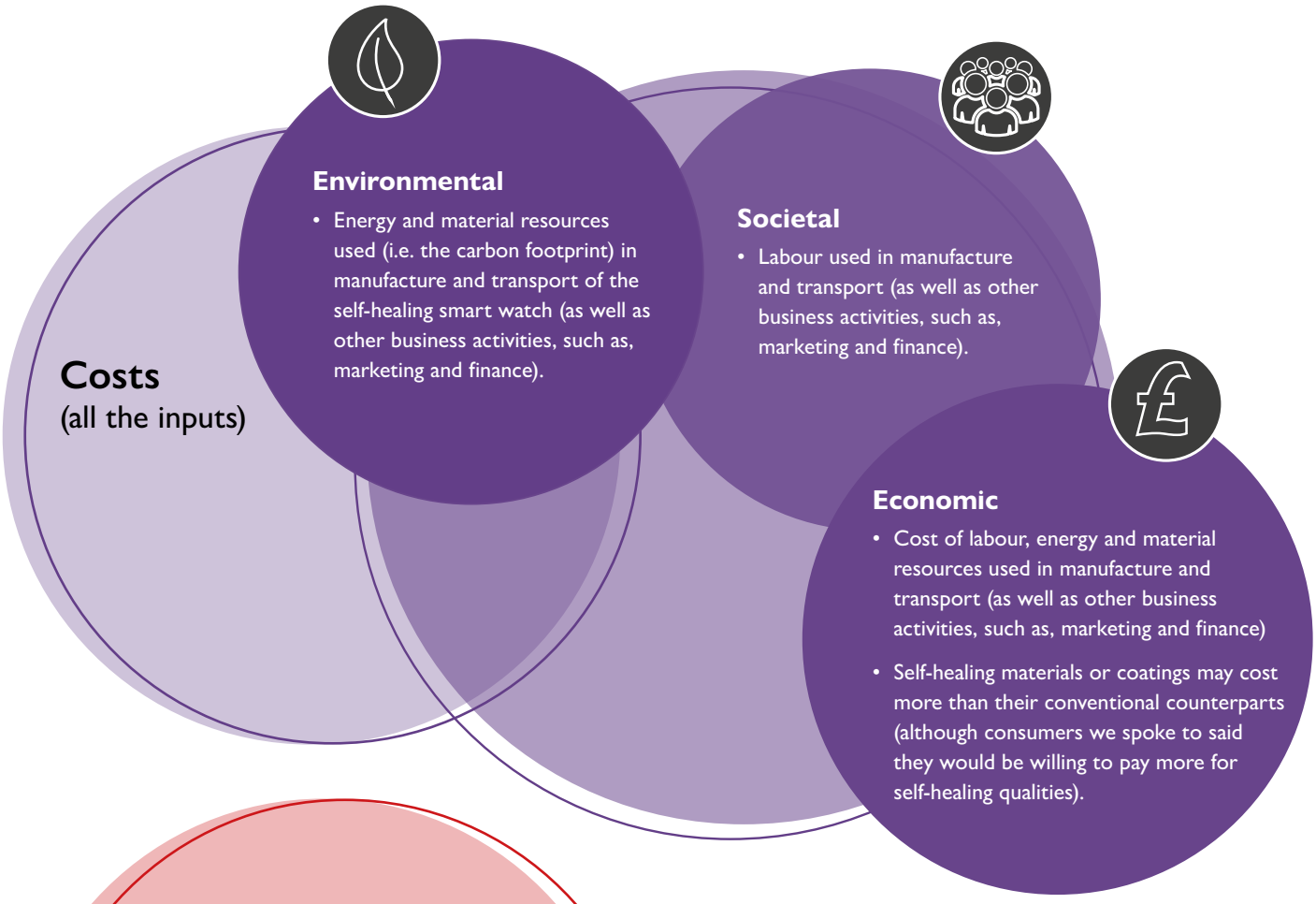
Our model can be applied to self-healing materials and products in order to understand the benefits they may offer, but also keep in mind the harm they may cause. It creates a rich and holistic picture of the value and impacts a product may have.

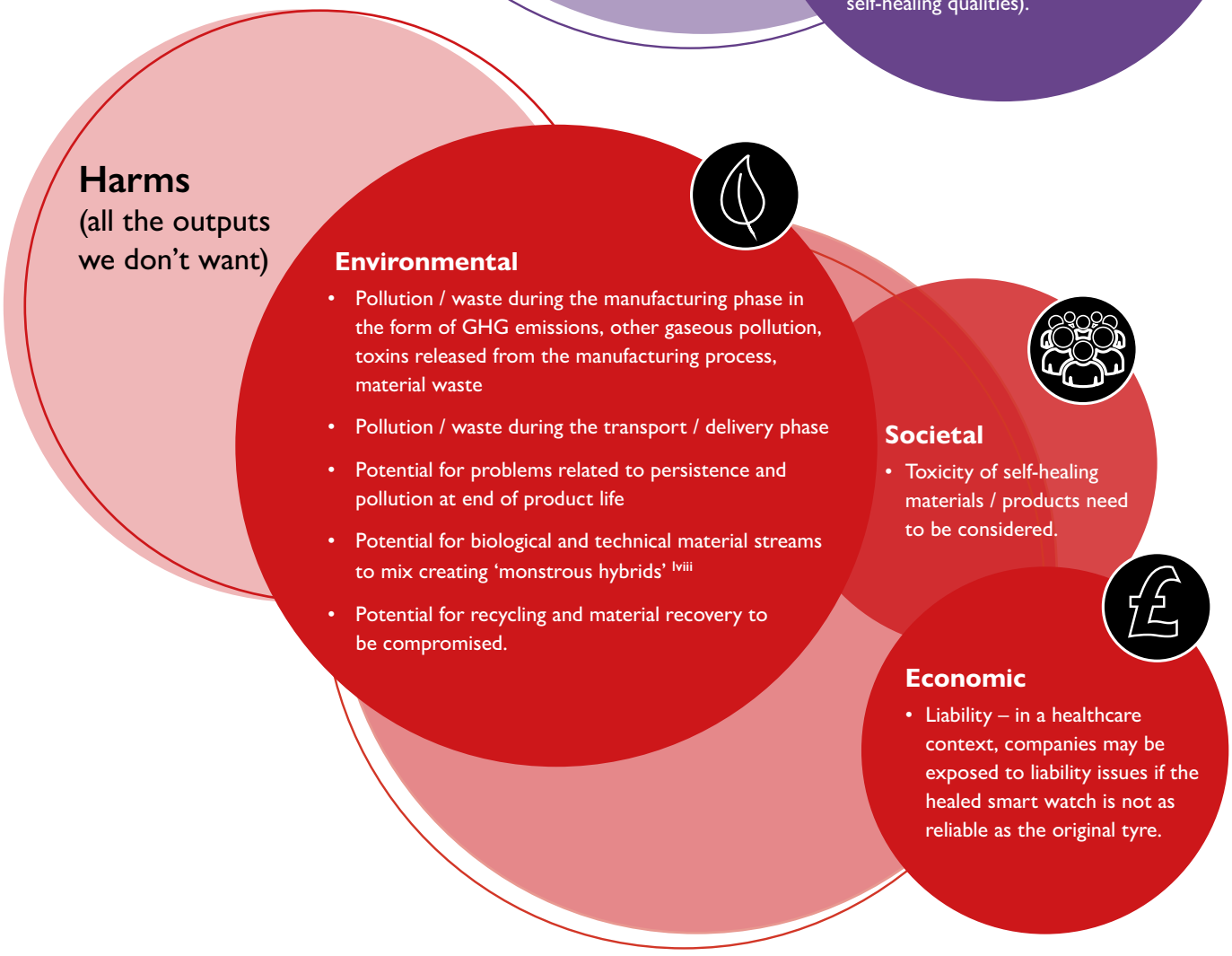
Figure 2: Adapted Ideality Framework



Benefits, Costs and Harms of Self-Healing Smartwatches




Costs
(all the inputs)
Environmental
• Energy and material resources used (i.e. the carbon footprint) in manufacture and transport of the self-healing smart watch (as well as other business activities, such as, marketing and finance).
Societal
• Labour used in manufacture and transport (as well as other business activities, such as, marketing and finance).
Economic
• Cost of labour, energy and material resources used in manufacture and transport (as well as other business activities, such as, marketing and finance)
• Self-healing materials or coatings may cost more than their conventional counterparts (although consumers we spoke to said they would be willing to pay more for self-healing qualities).


Harms
(all the outputs we don't want)
Environmental
• Pollution / waste during the manufacturing phase in the form of GHG emissions, other gaseous pollution, toxins released from the manufacturing process, material waste
• Pollution / waste during the transport / delivery phase
• Potential for problems related to persistence and pollution at end of product life
• Potential for biological and technical material streams to mix creating 'monstrous hybrids' [lviii]
• Potential for recycling and material recovery to be compromised.
Societal
• Toxicity of self-healing materials / products need to be considered.
Economic
• Liability – in a healthcare context, companies may be exposed to liability issues if the healed smart watch is not as reliable as the original tyre.

Conclusions and Recommendations

- Self-healing materials could play a crucial role in a transition to a Circular Economy through extending a product's lifespan, as well as improving safety and reliability.
- Circular Economy principles are becoming embedded within policy and legislative frameworks across the globe, for example, in the EU [lix], the UK [lx] and China [lxi].
- Large corporates are integrating circular thinking into their business: Cisco, Jaguar Landrover, Unilever, IBM, Siemens Mobility, Caterpillar, Rolls Royce [lxii].
- The European Investment Bank has invested over 2 billion Euros in Circular Economy projects in the past five years [lxiii] and there are now a number of public equity funds with a Circular Economy focus: BlackRock, BNP Paribas, Candriam, Cornerstone Capital Group, Credit Suisse (2 funds), DECALIA, Goldman Sachs, NN Investment Partners and RobecoSAM [lxiv].
- Our consultations with industry experts identified three key benefits of using self-healing materials to transition to a Circular Economy:
  - Extending product lifespan through maintaining aesthetic appeal as well as functionality, thereby reducing waste and keeping products, components and materials cycling in the system for longer.
  - Increasing ease of disassembly and reassembly and so enabling the modular design and easy-to-repair products.
  - Transition to circular business models, such as, product as a service by keeping products looking and functioning in premium condition for longer.
- Industry participants identified four key concerns which represent opportunities for future research:
  - Unwanted persistence of materials leading to pollution.
  - The creation of 'monstrous hybrids' in which 'technical' and 'biological' nutrients cannot easily be separated.
  - A greater understanding of safety and liability issues.
  - The limitations of self-healing materials in terms of a lack of capacity to heal larger damages.
- The majority of consumers we surveyed articulated an interest in the environmental credentials of products they bought and in self-healing materials, although there was a mixed response to the concept of circular business models, such as, rental rather than ownership.
- Consumers appreciated the potential benefits of self-healing materials within a Circular Economy, for example, to maintain a product's appearance and functionality, and to enable a consumer to keep a product for longer which is more convenient, especially in the context electronics which contain personal data.
- Our model to measure the costs and benefits of self-healing products in a Circular Economy combines the TRIZ Ideality Framework with a triple bottom line. When applied to the case study of self-healing smartwatches, it demonstrates benefits (such as, extended product life) as well as costs and potential harms (such as, mixing waste streams and creating 'monstrous hybrids').

Future Innovations

Self-healing materials are part of a wider group of 'smart' or animate materials which can change their properties and adapt to their environment [lxv].

Scientist are developing autonomous materials which are able to 'make decisions' in response to environmental change. The diagram below illustrates the continuous development of these products in relation to mobility and the Circular Economy.

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