Manufacturing Immortality
Self-Healing Materials in the Circular Economy

Case Study: Healthcare Systems

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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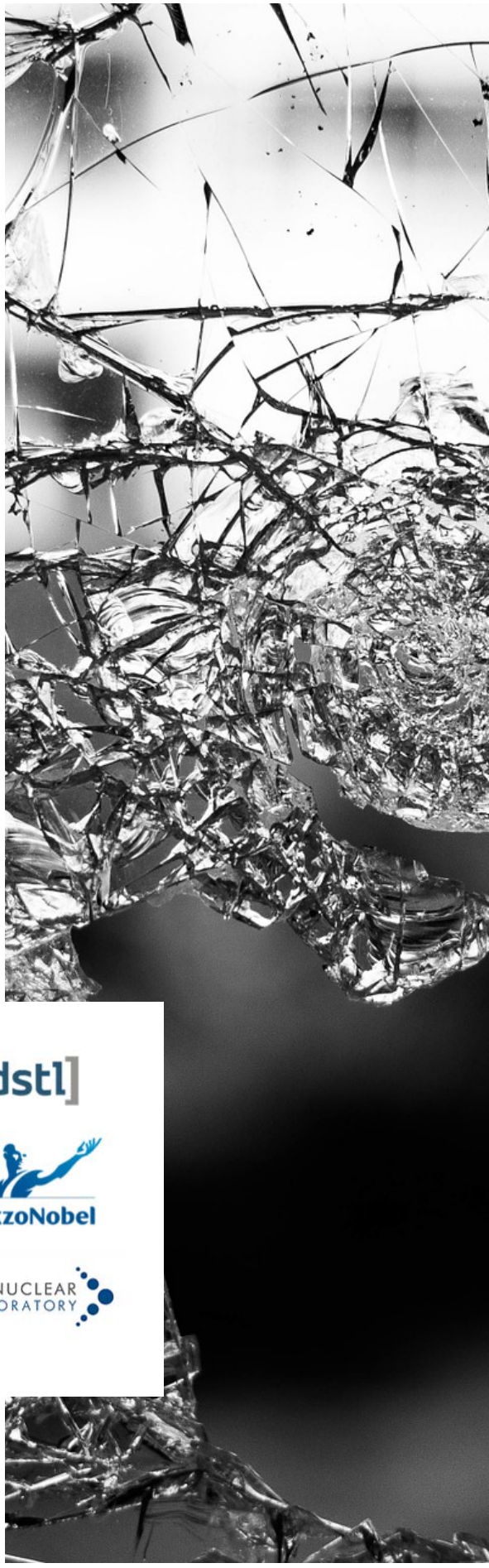
Introducing the Manufacturing Immortality Project



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

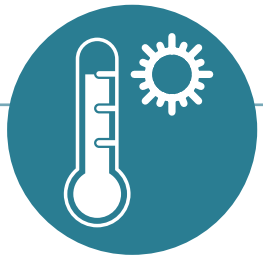
This case study illustrates the role self-healing materials can play as we move to a Circular Economy.

Climate Change is a Health Issue

‘Climate change is the biggest global health threat of the 21st Century.’

The Lancet and University College London Institute for Global Health Commission [i].

The health implications of climate change are well-documented. Since 2017, the Lancet Countdown has tracked the link between health and climate change on an annual basis [ii]. Its latest report (2020) [iii] outlines the health risks associated with climate change, including:

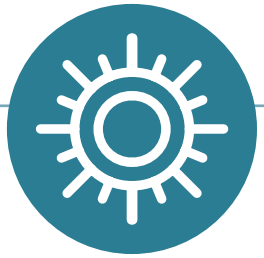


Heat-related deaths

Heat-related deaths in people aged over 65 have increased by more than 50% in past two decades, with almost 300,000 such deaths in 2018.

Wildfire

The number of days people are exposed to a very high or extremely high risk of wildfire has increased in 114 countries in the past 15 years, aggravating heart and lung conditions.



Drought

Increased risk of drought poses multiple dangers to health, for example, threatening drinking water supply and sanitation.

Floods

Localised flood events (which are becoming more frequent and intense due to climate change) may result in direct injury, the spread of infectious diseases and worse mental health outcomes, as well as threatening healthcare systems.

Increase in infectious diseases

Climate suitability for infectious disease transmission has been growing rapidly since the 1950s: dengue fever, malaria and vibrio bacteria, which cause a range of human infections, including gastroenteritis, wound infections, sepsis and cholera.

Global food security

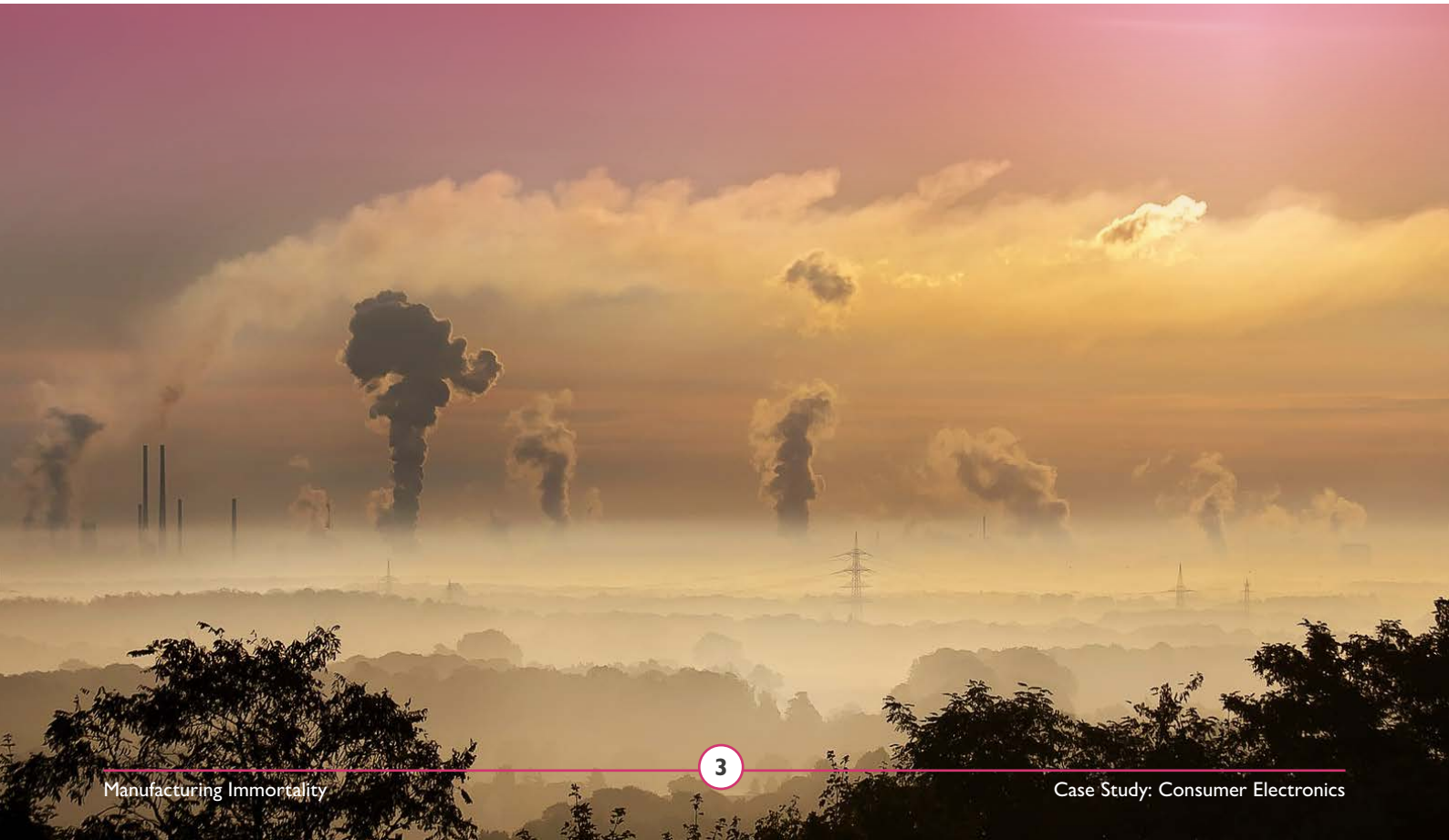
The number of people affected by hunger is rising, with 60 million more people affected between 2014 and 2019 [iv]. If this trend continues, this figure will exceed 840 million by 2030. Crop yields are threatened by the impacts of soil degradation and climate change – rising and variable temperatures, erratic rainfall, and extreme weather events, such as flooding and drought.

Livestock and poor diet

Emissions from livestock increased by 16% between 2000 to 2017, with ruminant livestock emissions representing 56% of total agricultural emissions, whilst increasingly unhealthy diets are becoming more common worldwide, with excess red meat consumption contributing to some 990,000 deaths in 2017 (an increase of 72% since 1990).

Air pollution

Many of the leading contributors to greenhouse gas emissions also contribute to air pollution which led to over 3 million deaths in 2018 (including 390,000 attributable to coal combustion): despite the growth of renewables, in 2018, the global energy supply from coal was 74% higher than in 1990 and global coal capacity continues to increase year on year.



Case Study:

Madagascar Famine 2021

Southern Madagascar is experiencing its worst drought in four decades causing more than 1.14 million people to experience food insecurity [v]. Of those, an estimated 14,000 people are already in catastrophic conditions (IPC Phase 5) and this is likely to double by October 2021 [vi]. This famine was widely reported as the first caused exclusively by climate change (rather than being politically driven) [vii].

'The impact of climate change is real on agricultural production and the lives of communities.'

Theodore Mbainaissem, Head of the World Food Programme (WFP) sub-office in Ambovombe, southern Madagascar [viii].

'Families are suffering and people are already dying from severe hunger. This is not because of war or conflict. This is because of climate change.'

David Beasley, The World Food Programme Executive Director [ix].

Climate Change: Threats to Infrastructure and Healthcare Systems

The effects of climate change, such as, extreme weather events will put public infrastructure and healthcare systems at risks. Globally, 67% of cities surveyed reported that they expected their public health assets and infrastructure to be seriously compromised by climate change [x].

Gloucestershire Floods, 2007[xi]

In 2007, Gloucestershire in the UK was flooded. Electricity substations were threatened which put electricity and water supplies at risk. Roads were also flooded making it extremely difficult to deliver pumps and other equipment to alleviate the flooding and mitigate its consequences. Usually, roads, electricity and public water supplies are uncorrelated and the potential for all three subsystems to fail simultaneously is unlikely. However, extreme weather events, such as, flooding, can simultaneously put multiple systems at risk. Keeping these systems fully functioning has implications for health *and* the ability to provide healthcare.

London Floods, 2021[xii]

In July 2021, the operations of two east London hospitals were compromised due to flash flooding. Whipps Cross hospital was left without power and had to evacuate 100 inpatients. Newham hospital was forced to shut its A&E department. These incidents demonstrate how increased risk of extreme weather events due to climate change has the potential to compromise and even incapacitate healthcare systems.

The Healthcare Sector's Role in Climate Change

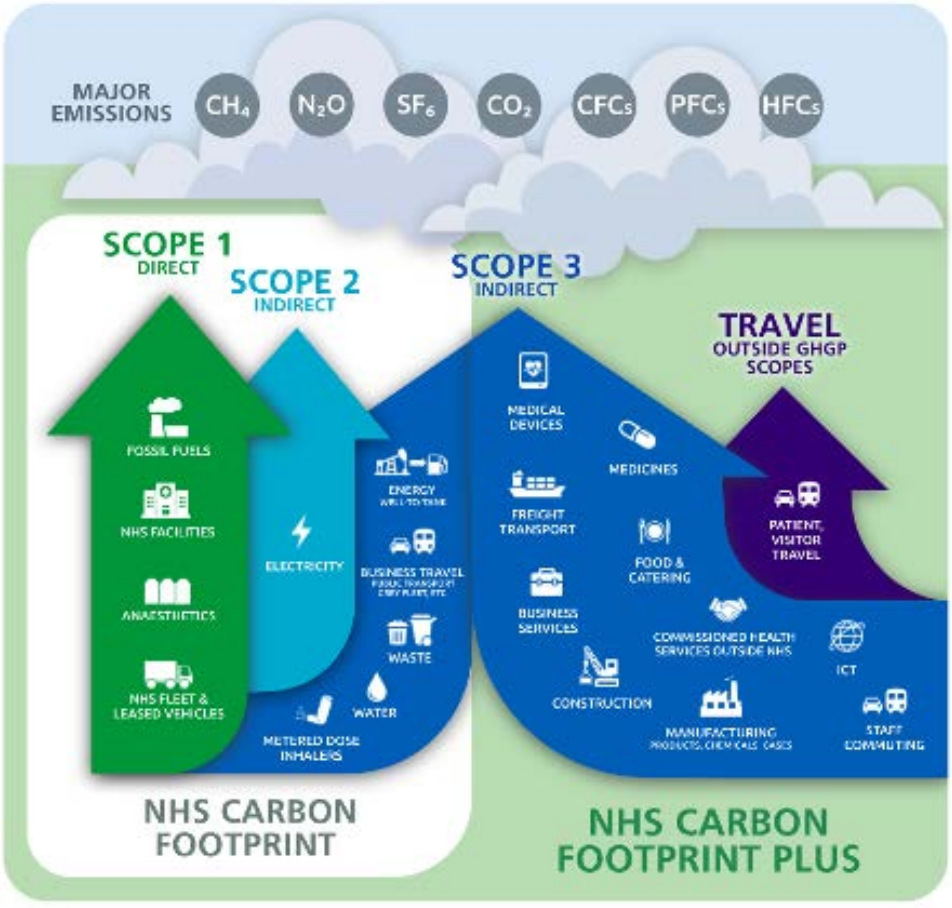
The Healthcare System Drives Climate Change

Globally, the healthcare system is responsible for 4.4% of greenhouse gas emissions [xiii]. If it were a country, it would be the fifth largest emitter [xiv]. Healthcare Without Harm's Green Paper, 'Healthcare's Climate Footprint' (2019) broke these emissions down into three scopes based on the Greenhouse Gas Protocol for corporate accounting and reporting: [xv, xvi]

Scope 1: Direct emissions from owned or directly controlled sources (such as healthcare facilities and vehicles) – make up 17% of the sector's worldwide footprint.

Scope 2: Indirect emissions from the generation of purchased energy, mostly electricity – comprise another 12%.

Scope 3: All other indirect emissions that occur in producing and transporting goods and services, including the full supply chain (such as pharmaceuticals and other chemicals, food and agricultural products, medical devices, hospital equipment, and instruments) – 71% of emissions.



Source: Delivering Net Zero NHS (p. 11)

Do No Harm

'More intense storms and floods, more frequent heatwaves and the spread of infectious disease from climate change threaten to undermine years of health gains.' **NHS England** [xvii].

'The healthcare sectors' oath to 'do no harm' cannot solely focus on treating the mass of patients descending through their doors amidst a pandemic, heatwave, or disastrous hurricane. If the sector is to remain viable, it must play a far larger role – addressing the conditions that perpetuate these public health disasters.'
Gary Cohen, founder of Health Care Without Harm and Practice Greenhealth [xviii].

'The world's health sector facilities churn out CO_2 through the use of significant resources and energy-hungry equipment. Places of healing should be leading the way, not contributing to the burden of disease.'
Tedros Adhanom Ghebreyesus, Director General, World Health Organization [xix].

'The health profession [has] the responsibility to act as public health advocates… ensuring climate change is understood as being central to human wellbeing.'
The Lancet Commission on Health and Climate Change [xx].

Actions from National Healthcare Providers Worldwide[xxi]

48%

48% of countries surveyed have assessed national vulnerability and adaptation for health.

At least 51

At least 51 countries have developed health and climate change strategies (although only four reported having adequate national funding available to fully implement these plans).

109

109 countries have reported medium-to-high implementation of a national health emergency framework in preparation for a multi-hazard public health emergency.

86

86 countries' healthcare systems have connected with their equivalent meteorological services to facilitate climate change mitigation and adaptation.

$42b

$43 billion divested from fossil fuels by health institutions between 2008 and 2019.

National Health Service (NHS) in the UK

The NHS is the largest single-payer (public) healthcare system in the world and has an annual budget of £134 billion [xxii]. With 1.5 million employees, it is the single largest employer in Europe.

The Sustainable Development Unit was founded in 2008 to ensure the NHS met its commitments under the UK Climate Change Act (i.e. to ensure greenhouse gas emissions in 2050 are at least 80% of the 1990 baseline). This has entailed tracking, reporting, and reducing the NHS's carbon footprint. The Health and social care carbon footprint has been reduced by 18.5% since 2007 [xxiii] and the NHS carbon footprint is estimated to 62% of 1990 levels [xxiv].

Delivering a Net Zero NHS

In 2020, the NHS set out ambitious net zero targets, aiming to be the world's first net zero national health service. Employing Circular Economy principles are fundamental to this.

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 [xxv].

Policymakers, investors and industry are moving away from a 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 [xxvi, xxvii, xxviii, xxix, xxx].

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.

'As a health technology company, it is our ambition to be a leading circular company, decoupling growth from resource consumption across the value chain – shifting from products to solutions, and maximising value for customers, patients and planet by responsively and proactively managing the lifecycle of our solutions. Circular design is central to that endeavour.'

Robert Metzke, Philips Global Head of Sustainability [xxxi].

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 [xxxii].

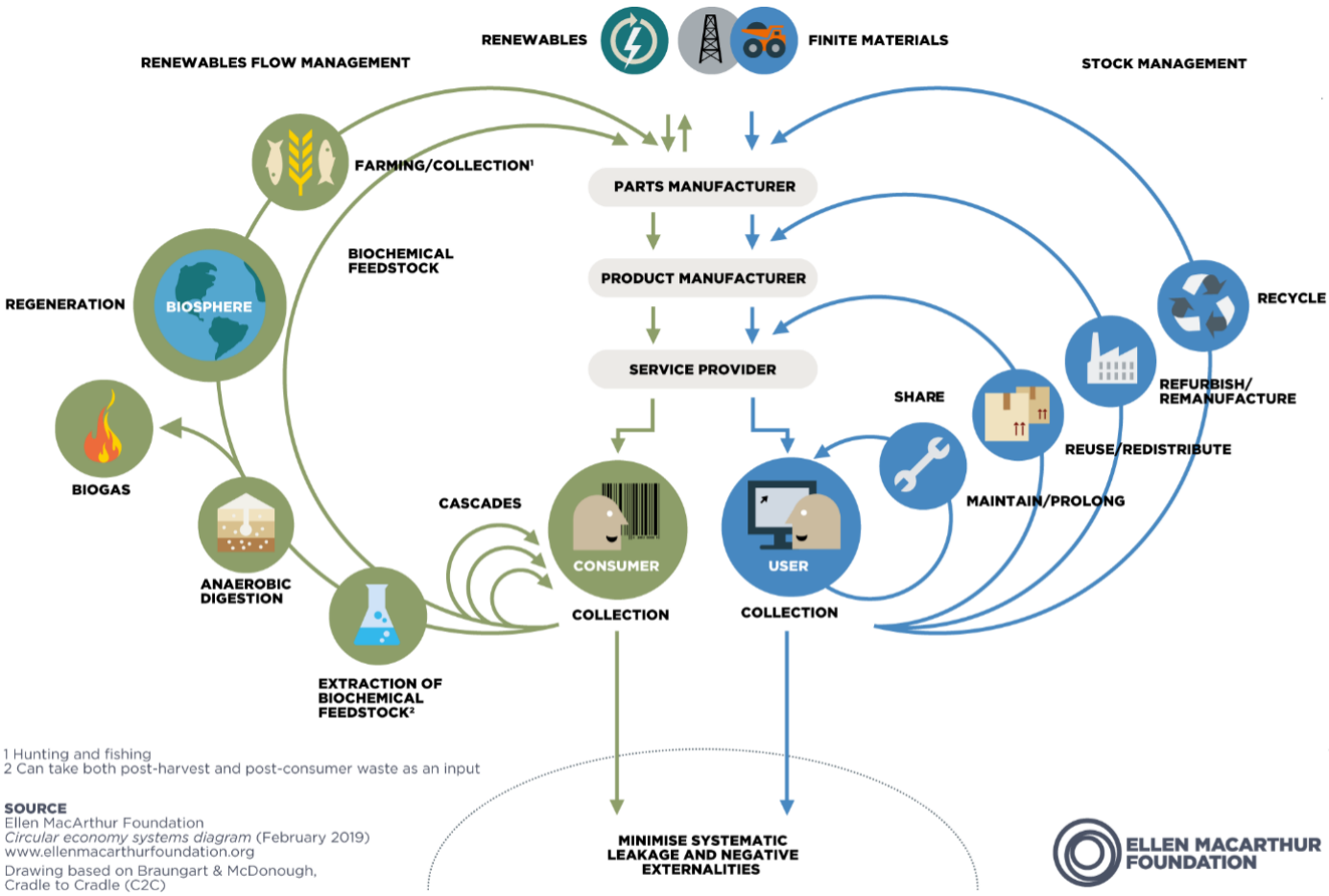
Restorative and Regenerative

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 [xxxiii].

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 [xxxiv].

'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 [xxxv].

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 [xxxvi]), as well as improving safety and reliability [xxxvii].

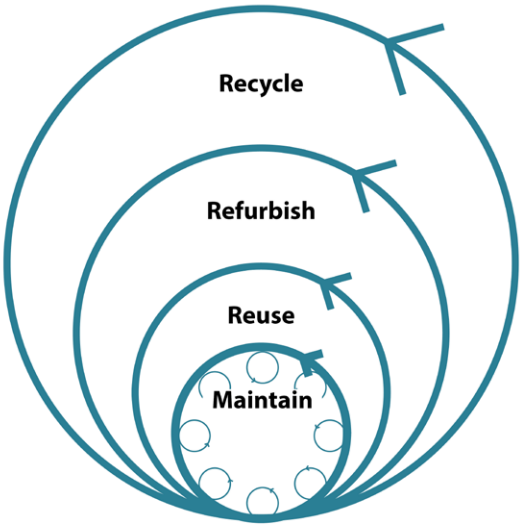
Self-healing materials and coatings can contribute to product life extension in the following ways:

- By helping to restore functionality. Hydrogels, concrete, glass, asphalt or polymers with small cracks or defects could repair themselves. There are many applications for these types of self-healing materials, such as buildings, roads, pavements, fuel cells, printed circuit boards and consumer electronics. Some self-healing products are already commercially available, such as, bio-active glass used for orthopaedic and dental surgery [xxxviii, xxxix].
- 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 fridges, ovens and cookers, as 'consumers are looking for durable surfaces that look premium and are easy to clean' [xl].

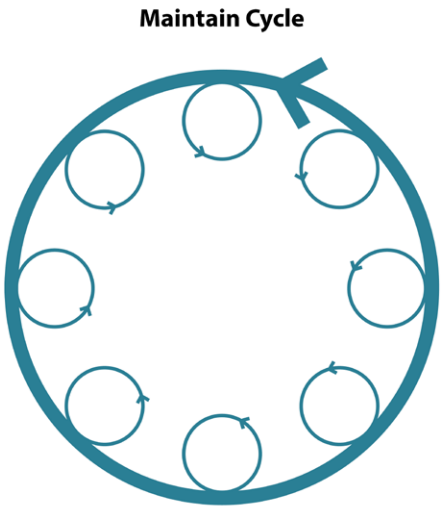
Some applications could improve **both aesthetics** and **functionality**, for example, self-healing coatings on metal infrastructure like bridges, could help to protect the metal and reduce corrosion. Given the worldwide cost of corrosion has been estimated to be nearly $300 billion per year, this could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

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 [xlii]



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.

Hydrogels

Our research team at the **University of Bristol** have developed a self-healing hydrogel using an enzyme called lysyl oxidase (or LOX), which is found within the human body and is responsible for maintaining and repairing our skin. One application for this new hydrogel could be within synthetic skin. Currently being suggested for prosthetics or wound dressing, they are not currently able to self-repair, however the introduction of LOX could enable healing of these devices to occur. (A detailed cost/benefit analysis of this material can found **below**).

Glass

Our researchers at **Sheffield-Hallam University** have developed a low-cost radiation resistant glass and our team from Northumbria University are exploring coating the glass with a self-healing material to improve scratch resistance. Applications for this glass are in environments where extreme radiation resistance is crucial, such as, medical applications, within the space and nuclear industries, as well as within the energy sector (solar panels) or everyday products (glasses, cameras or mobile phone screens).

Polyurethane

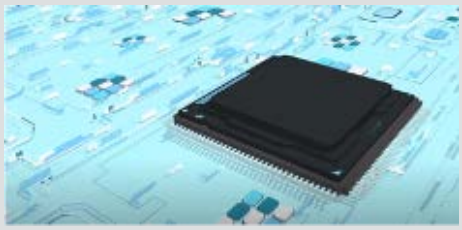
Our researchers from **Northumbria University** have developed an **intrinsically self-healing polyurethane**: the intermolecular bonds can be reattached, a bit like Velcro. The material is being developed so that it can be moulded into different components and products and could have many applications, particularly in areas where products are inaccessible or costly to repair (such as within the human body or in space).

Watch our animations on YouTube to find out more:

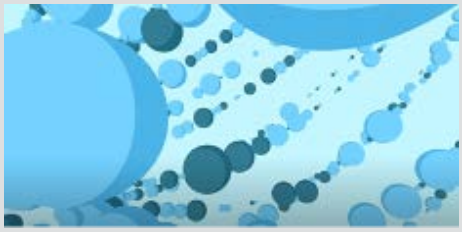
Understanding the sustainability benefits and uses for self-healing materials and products

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 [xliii].

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 [xliv].

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' [xlv]. 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.

Self-healing Materials in a Net Zero NHS

Clinical Applications

eries will not just be used in consumer electronics but in Our research has identified a range of clinical applications for self-healing materials within healthcare, including:

- Wound dressings
- Tissue adhesives (replacing sutures) [xlvi]
- Tissue engineering and prosthetics: synthetic skin [xlvii], tissue repair [xlviii], artificial muscles [xlix], prosthetic limbs [l],
- Implantable electronic devices [li]

The use of self-healing materials in these applications could have positive environmental impacts, reducing waste and the use of resources, thereby reducing carbon emissions. Additional benefits are cost, safety and patient experience: implants such as pacemakers or prosthetic joints can be both very costly and pose great risk to human life if they need removing or repairing [lii]. Thus, materials that have enhanced durability and can repair at a molecular level as stresses occur would be highly beneficial [liii].

Reducing the need for medical intervention and demand on NHS services (for example, through preventative medicine, lifestyle changes and the **Getting It Right First Time** programme) is a key element of the NHS net zero strategy. Self-healing materials could contribute to reducing emissions through reducing patient contact time with clinicians.

> 'Self-cleaning and self-repairing materials that strengthen with stress would be amazing'.
>
> **Participant working within orthopaedics [liv].**

Decarbonising the Supply Chain[lv]

Bio-Based Polymers

The NHS aims to actively identify and embrace low-carbon technologies and innovations, such as, bio-based polymers, which are fully biodegradable and therefore, reduce waste and environmental impact. The adoption of these materials within single use products is particularly important.

Self-healing compositions of bio-based polymers are being developed, such as the **LOX based hydrogel** developed at University of Bristol as part of the Manufacturing Immortality Project. (A detailed cost/benefit analysis of this material can found **below**). This will further reduce environmental impacts through extending product life. Patient contact time with the NHS would also be reduced, with the additional benefits of improving patient satisfaction and reducing demand on services.

Refurbishment and Reuse

Over 1.4% of supply chain emissions are due to single-use devices, some of which could be refurbished and reused, saving the NHS both carbon and money [lvi]. Self-healing materials could facilitate this. One application could be enabling the design of modular, easy-to-repair products. Self-healing seals could be fitted around each module, facilitating assembly and disassembly: once reassembled the seal could simply be pressed together to self-heal.

Walking Aid Refurbishment

The NHS has committed to expanding existing walking aid refurbishment schemes, with 40% of all walking aids refurbished in the next five years. Self-healing materials could support with this endeavour through minor defects being repaired autonomously.

Cleaning, Disinfection and Sterilisation

For self-healing materials to be used in medical devices and equipment, further research is needed to understand how they would respond to cleaning, disinfection and sterilisation processes (such as, washing, steam sterilisation, intense heat, UV light or chemical processes) to ensure compliance with medical device manufacture regulations. Reprocessing procedures (including cleaning, disinfection and sterilisation) need to be considered at the design phase of self-healing medical devices to ensure that devices are fully compatible with all the constraints and processes. Consideration would need to be given as to whether the inclusion of self-healing materials would complicate cleaning, disinfection, and sterilisation processes and therefore, have cost implications.

Estates and Facilities: On Site Renewables [lvii]

Emissions from NHS estates and facilities comprise 15% of the total carbon emissions profile. To combat this and increase resilience of its power supply, the NHS is shifting to on-site renewable energy and heat where possible, with a commitment to purchase 100% renewable energy from April 2021. Royal Manchester Children's Hospital has invested in an on-site renewable energy project and saved £80,000 in lifetime energy costs. Installation of photovoltaics across the entire NHS estate would reduce the NHS Carbon Footprint by 1.6%. Self-healing materials could be employed within these in order to extend the lifespan of the product and improve performance and reliability. Our work on self-healing and radiation resistant glass could support this transition.

Self-Healing Fuel Cells

Polymer electrolyte (PEM) fuel cells use hydrogen gas and air to produce electricity. These can be built in a range of different sizes for various applications, such as powering electric vehicles (EVs) or providing a back-up power supply to hospitals or medical equipment.

As part of the Manufacturing Immortality project, researchers at Lancaster University have been developing self-healing materials which can be used to make the membranes within hydrogen fuel cells. These membranes are very delicate and if they become damaged it impacts on the efficiency and lifespan of the fuel cell. Manufacturing this membrane from a self-healing material can improve the reliability and lifespan of the product.

Watch our YouTube animation to find out more:

Self-healing membranes for fuel cells

Travel and Transport [lviii]

Approximately 3.5% of all road travel in England relates to patients, visitors, staff and suppliers to the NHS, contributing around 14% of the system's total emissions.

The NHS has committed to the electrification of its transport fleet, including developing and testing the world's first hydrogen-electric hybrid double-crewed ambulance through the London Ambulance Service as part of project ZERRO (Zero Emission Rapid Response Operations Ambulance), funded by Innovate UK.

Self-healing products (such as tyres, paints and fuel cells) can play a key role reducing emissions in the transport sector through extending product life and improving reliability and safety, as well as enabling a transition to circular business models, like products as a service, which incentivise circular design. For more on the role of self-healing materials in the mobility sector, see our case study: 'Circular Mobility Systems'.

Circular Business Models in Healthcare

Circular Supplies

The Circular Supplies business model is based on the use of fully renewable, recyclable, or biodegradable resources [lix].

Within the healthcare sector, this can be facilitated through the use of bio-based materials and the switch to renewables for building energy requirements and transport. It is crucial in reducing the environmental impact of single-use items. The addition of self-healing materials into this model reduces the number of single-use items needed (by extending product lifespan), further reducing waste and emissions.

Products as a service

This model involves manufacturers moving away from selling a physical product or system to offering its use as a service i.e. 'servitisation'. The healthcare sector, in particular medical devices, is an area especially particularly well-suited to this business model for three reasons [lx]:

1. Within the healthcare sector, it is vital that a service is provided continuously – the non-stop availability of medical devices (or backups) is crucial.
2. Guaranteeing a device's level of performance (in terms of safety and functionality) is equally important.
3. Contract types are often integrated to include device updates and operator training.

There is potential for all stakeholders to benefit [lxi]:

- Manufacturers: receive continuous revenues for the lifetime of the device
- Hospitals: move away from high upfront capital expenditures to operational expenditure
- Staff, patients and community: performance of equipment is guaranteed and access to expensive, high-quality devices is improved.

Business models based on servitisation incentivise manufacturers to use circular design principles to produce products that are durable and can easily be repaired, reused or recycled, contributing to the sustainable use of resources and better environmental outcomes.

Self-Healing Materials in Servitisation Business Models

Materials developed on the Manufacturing Immortality Project might be used to extend product life, for example, self-healing polymers or low-cost radiation resistant glass treated with a self-healing coating. Self-healing polymers can be used to facilitate the design and production of modular devices which can be repaired easily through the use of a self-healing seal around each module.

Philips Enterprise Monitoring as a Service (EMaaS) Model [lxii]

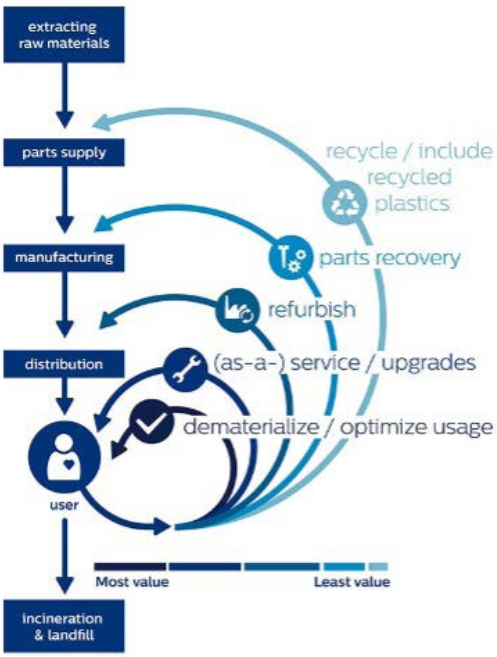
In a partnership with Jackson Health System, Philips has developed a patient monitoring system offered through the Enterprise Monitoring as a Service (EMaaS) Model. Rather than hospitals buying and owning the system outright, the ownership remains with Philips. A key advantage for the hospital is that there is no need for an initial capital outlay. The manufacturer (Philips), rather than the hospital, is responsible for performance management, including maintenance, repairs and upgrades. The customer (hospital) pays a per-patient fee for a guaranteed service.

'Working together, we have developed the EMaaS model, which provides them [the hospital] with a state-of-the-art, scalable patient monitoring solution that reduces their per capita cost of care, while allowing them to improve the patient and staff experience.'

Vitor Rocha, Chief Philips North America and member of the Executive Committee, Royal Philips [lxiii].

Defibrillators

Companies such as **Defib Machines** in the UK offer defibrillators on a rental basis. This increases accessibility for communities and (as they are lower value compared to other hospital equipment) enables short term access contracts.



Source: Why circular design is essential for better healthcare – Blog | Philips

Platforms for Medical Device Circulation [lxiv]

Selling platforms, such as Promed and DOTmed, facilitate the purchase of pre-owned medical equipment. Sharing platforms, such as, Cohealo and Floow2, enable sharing and peer2peer renting, helping to address the issue of underused devices and equipment, as well as constrained healthcare budgets. Floow2 has worked with the Canadian Coalition for Green Health Care (CCGH) to create **Health-Share** which enables excess stock to be resold or redistributed. Self-healing materials could play a role within these models by extending product life and improving aesthetic resilience, thereby facilitating consumer confidence.

'We hope to improve the overall stewardship of scarce health care resources. Everybody wins when we connect with others to share expensive, difficult to source items.'

Neil Ritchie, Executive Director CCGH.

Consumer and Industry Perspectives

Feedback we gathered from industry and consumers suggests there is a role for self-healing materials within circular business models:

'a self-healing surface that keeps products looking good for longer' would be of great interest.

'A rented self-healing product could be guaranteed to be in better condition than a regular one. It could be potentially cheaper given that it might not require much servicing.'

Case Study:
Self-Healing Bio-Based Hydrogels

As part of the Manufacturing Immortality Project, a research team at the University of Bristol has developed a bio-based self-healing hydrogel through the inclusion of a microbial version of the enzyme, LOX (lysyl oxidase). This enzyme is responsible for repairing and maintaining skin which it does by helping to create strong covalent bonds (or crosslinks), between collagen fibres in our skin, and the ligaments in our muscles, allowing our skin to maintain its strength, flexibility and self-healing ability.

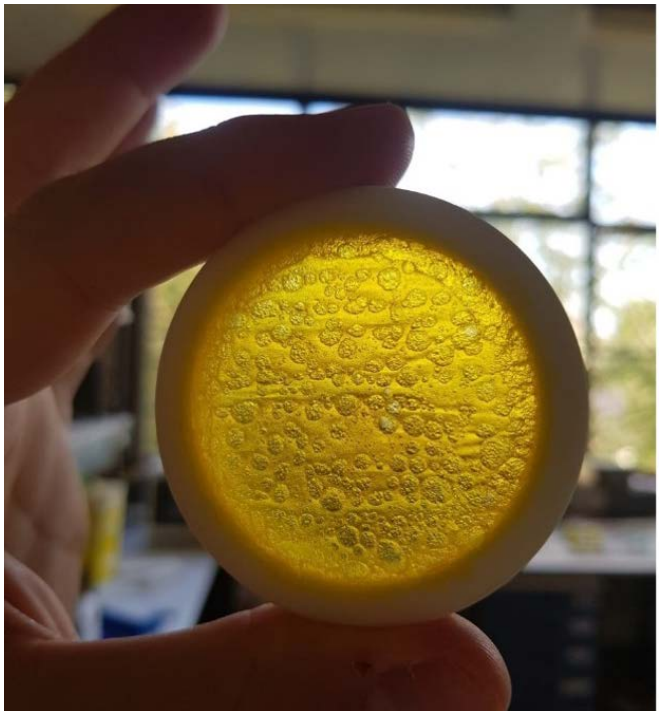
Traditionally, the use of LOX in materials has been impeded by low yields and difficult expression protocols. However, a new procedure developed at University of Bristol allows us to produce LOX at much higher yields than previously reported.

This ultimately expands the scope for LOX to be applied to many different materials, leading to a new era of self-healing, bio-hybrid materials that not only have longevity and increased durability, but also contribute to sustainable manufacturing methods.

One use for this technology is within synthetic skin. Currently, polylysine-based hydrogels are being suggested for prosthetics, however if damaged are not able to self-repair. With the addition of LOX, these hydrogels can potentially self-heal. Other possible uses for bio-based, self-healing hydrogels are as wound dressings, sutures and other forms of tissue engineering.

The material developed by the University of Bristol team has a range of advantageous features. It is:

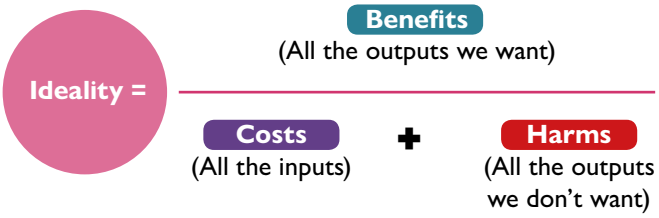
- Immunogenic
- Non-toxic
- Anti-bacterial
- Bio-compatible
- Self-healing (extending its lifespan and reducing the need for medical intervention)
- Bio-based (fully biodegradable and environmentally safe)



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 [lxv]. We built on existing models and metrics (such as, the Life Cycle Assessment (LCA) [lxvi], the Material Circularity Indicator (MCI) [lxvii], the Durability Index,[lxviii] Cost-Benefit Analysis [lxix]) and in particular, drew heavily on the TRIZ (Theory of Inventive Problem Solving) Ideality framework [lxx] (see Figure 1):

Figure 1. TRIZ Ideality Equation [lxxi]

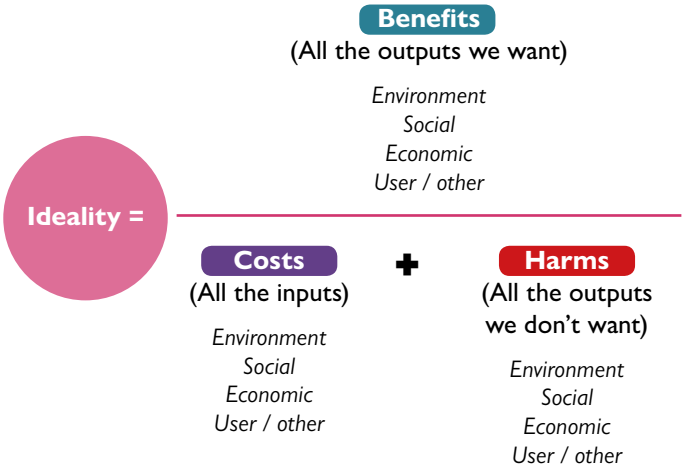


The advantage of this model is that it explicitly articulates the harm that a product or scenario can cause. This forces the producer / user to confront harms, rather than viewing them as 'externalities' for which they have no responsibility. Models or systems which lack an explicit articulation of harm 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. For example, in the UK, the National Health Service (NHS) meets the cost of noncommunicable diseases in which the consumption of products (such as, cigarettes, alcohol or highly processed foods) are key risk factors [lxxii].

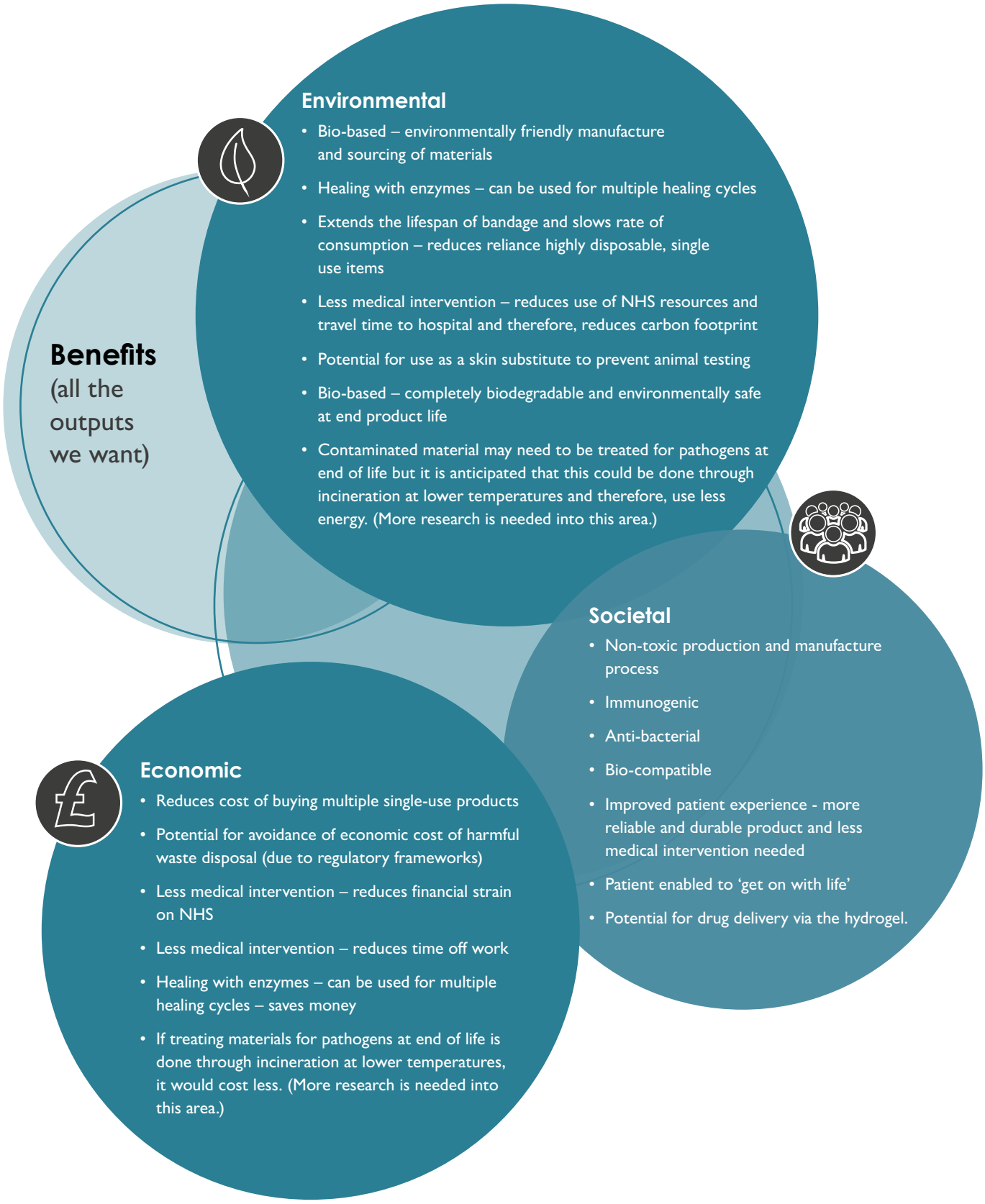
Our model combines the Ideality Framework with a triple bottom line (social, environmental and economic impacts) (see Figure 2). It has potential to integrate both quantitative and qualitative measures. For example, a quantitative metric may be used to measure the extent of self-healing or 'healing efficiency' (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 [lxxiii]. Qualitative measures may be important to assess consumer attitudes and more value-based perspectives.

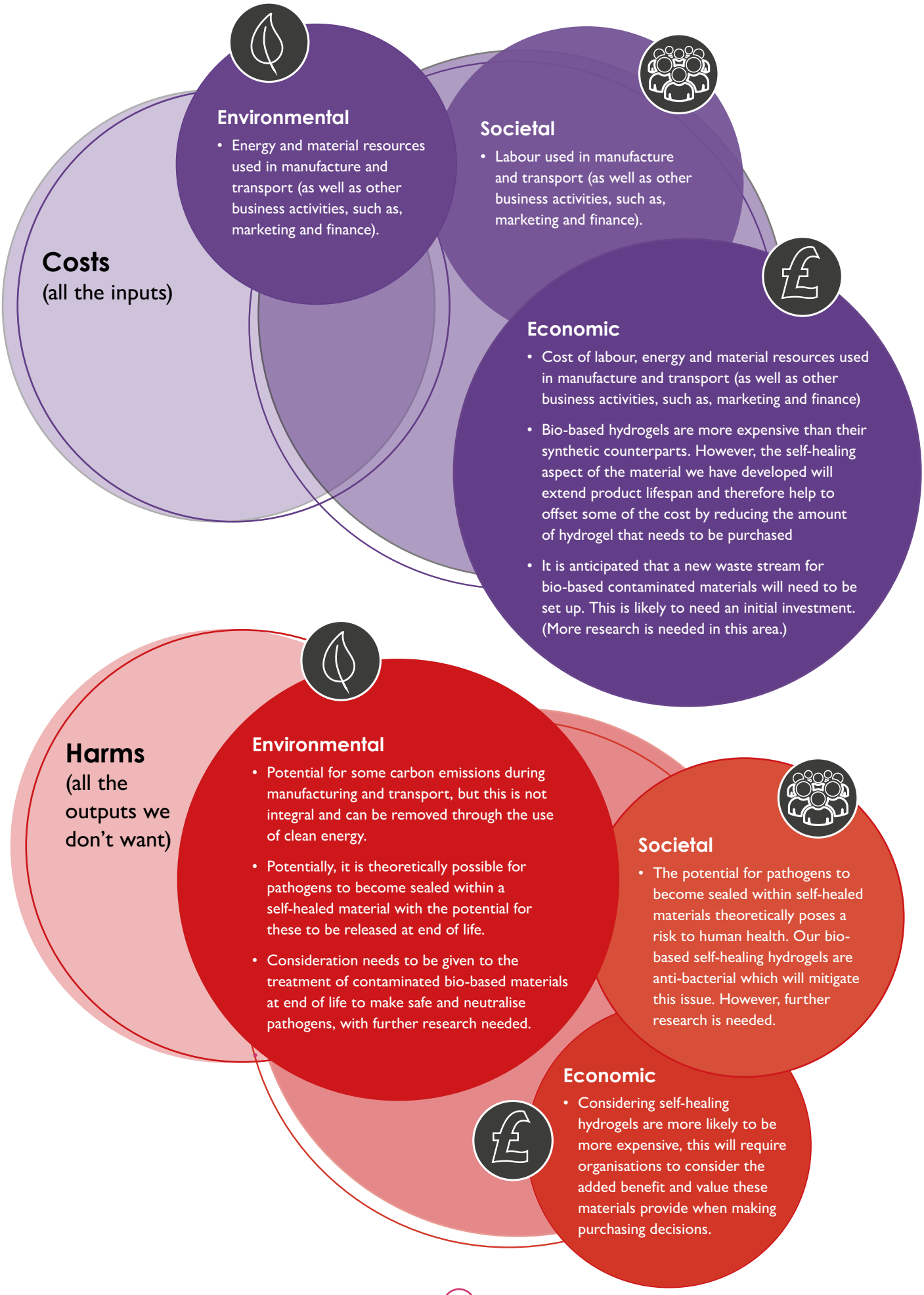
Our model can be applied to self-healing materials and products in order to understand the benefits they may offer, but also keep in mind the harm they may cause. It creates a rich and holistic picture of the value and impacts a product may have.

Figure 2: Adapted Ideality Framework



Benefits, Costs and Harms of Self-Healing Bio-Based Hydrogel




Costs
(all the inputs)
Environmental
• Energy and material resources used in manufacture and transport (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)
• Bio-based hydrogels are more expensive than their synthetic counterparts. However, the self-healing aspect of the material we have developed will extend product lifespan and therefore help to offset some of the cost by reducing the amount of hydrogel that needs to be purchased
• It is anticipated that a new waste stream for bio-based contaminated materials will need to be set up. This is likely to need an initial investment. (More research is needed in this area.)
Harms
(all the outputs we don't want)
Environmental
• Potential for some carbon emissions during manufacturing and transport, but this is not integral and can be removed through the use of clean energy.
• Potentially, it is theoretically possible for pathogens to become sealed within a self-healed material with the potential for these to be released at end of life.
• Consideration needs to be given to the treatment of contaminated bio-based materials at end of life to make safe and neutralise pathogens, with further research needed.
Societal
• The potential for pathogens to become sealed within self-healed materials theoretically poses a risk to human health. Our bio-based self-healing hydrogels are anti-bacterial which will mitigate this issue. However, further research is needed.
Economic
• Considering self-healing hydrogels are more likely to be more expensive, this will require organisations to consider the added benefit and value these materials provide when making purchasing decisions.

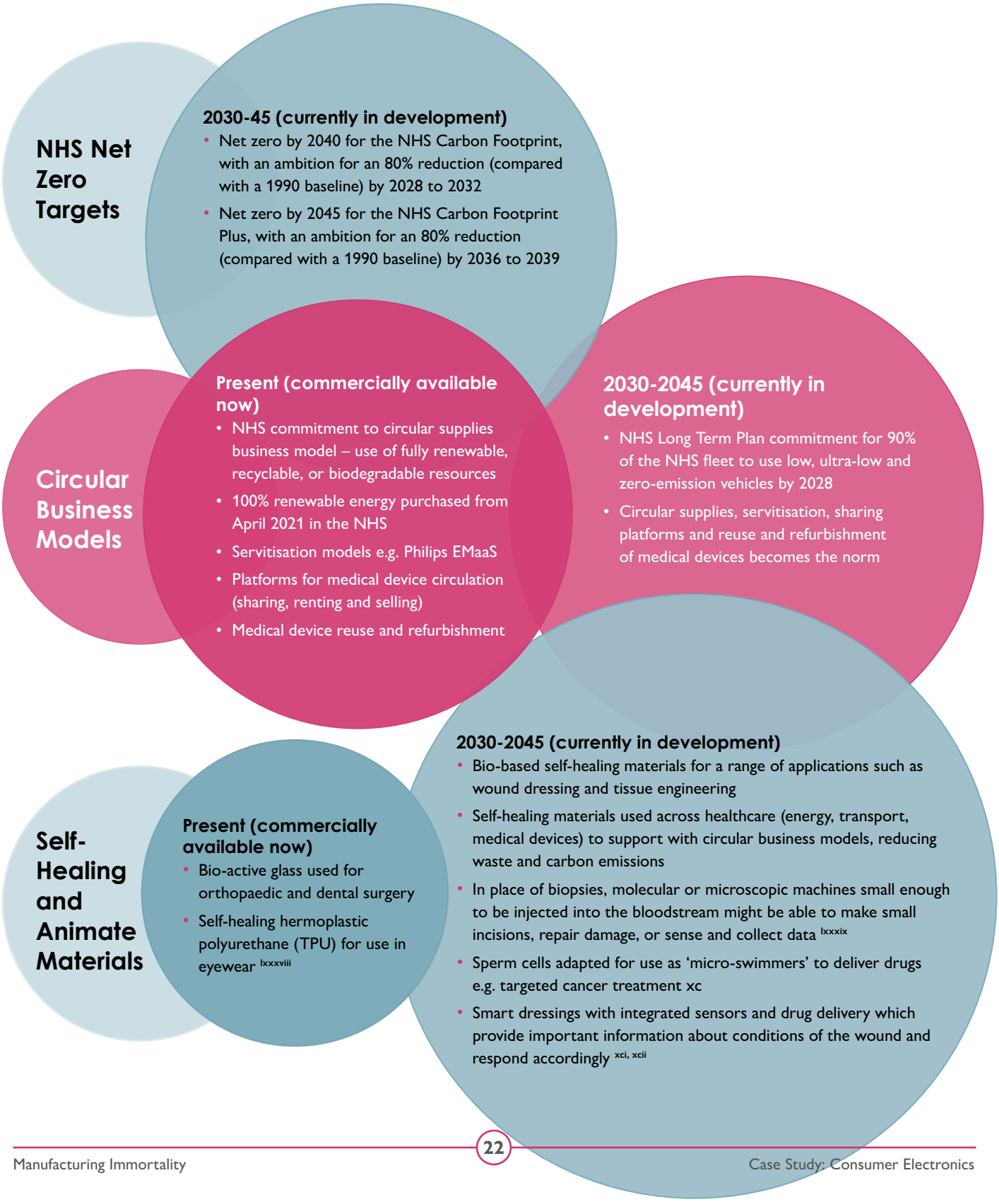
Conclusions and Recommendations

- Globally, the healthcare sector is recognising the link between climate change and health, and that its commitment to 'do no harm' must also extend to reducing carbon emissions within the sector, exemplified by the NHS's net zero strategy.
- Our research has identified a range of applications for self-healing materials within the healthcare sector which can support to a transition to a Circular Economy through extending product lifespan, and thereby reducing waste and carbon emissions:
  - Clinical applications: wound dressings; tissue adhesives (replacing sutures) [lxxiv]; tissue engineering and prosthetics [lxxv, lxxvi, lxxvii, lxxviii] and implantable electronic devices [lxxix]
  - Refurbishment and reuse of medical devices, for example, through enabling modular design
  - Walking aids
  - Photovoltaics cells for on-site renewable energy
  - Hydrogen fuel cells to provide back-up power on-site or to power an electric fleet
  - Self-healing tyres, paints and fuel cells within healthcare fleets
- Self-healing materials can be used to facilitate the transition to circular business models:
  - Circular supplies: the development of bio-based self-healing materials can support a transition to the use of biodegradable resources [lxxx]
  - Servitisation: a model ideally suited to the provision of high-value medical equipment – the use of self-healing materials can be used to extend product lifespan in terms of functionality and aesthetics.
  - Medical device circulation (through renting or sharing platforms): self-healing materials can be used to facilitate this model through extending product lifespan (both functionality and aesthetics).
- Using the enzyme LOX, our research team at the University of Bristol has developed a self-healing bio-based hydrogel which has multiple benefits:
  - Immunogenic
  - Non-toxic
  - Anti-bacterial
  - Bio-compatible
  - Self-healing (extending its lifespan and reducing the need for medical intervention)
  - Bio-based (fully biodegradable and environmentally safe)
- 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 bio-based hydrogel, it demonstrates multiple benefits (as above), no identifiable harms and although there is a higher financial cost, this will be counterbalanced by an extended product lifespan.
- Circular Economy principles are becoming embedded within policy and legislative frameworks across the globe, for example, in the EU [lxxxi], the UK [lxxxii] and China [lxxxiii].
- Large corporates are integrating circular thinking into their business (including within the healthcare sector): Philips, Cisco, Jaguar Landrover, Unilever, IBM, Siemens Mobility, Caterpillar, Rolls Royce [lxxxiv].
- The European Investment Bank has invested over 2 billion Euros in Circular Economy projects in the past five years [lxxxv] 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 [lxxxvi].

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 [lxxxvii].

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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