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# Self-Healing Materials in a Circular Economy

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**Keywords**: Self-Healing Materials; Product Longevity; Circular Economy; Repair; Product Design.

**Abstract**: There are materials currently being developed that have the ability to self-healing or self-repair. While from a materials innovation perspective this technology delivers new and interesting functionalities, for product lifetime extension research, this provides an exciting opportunity to explore how this might facilitate product longevity. Utilising a literature review, this paper investigates what are the key benefits that self-healing material might offer product lifetime extension. Considering two main perspectives of product longevity, i.e. technical and service lifetime, five key benefits were identified. It is proposed that self-healing systems can help to: *Enhance Physical Durability, Maintain Efficiency, Increase Reliability, Enhance Aesthetic Resilience* and *Reduce Cost and Risk of Future Repair*. Lastly, to fully validate these factors future research and field testing of these technologies would need to be conducted to fully realise their product longevity potential.

## Introduction

Inspired by biological systems, there is a new category of smart materials that have an intrinsic ability to restore functionality after being damaged (Diesendruck et al., 2015; Bekas et al., 2016). Referred to as self-healing or self-repairing, these materials can recover and repair themselves in response to aesthetic or structural damage, either autonomously utilising inherent functional capabilities or through external triggers (Ghosh, 2009; Aissa, et al., 2012).
Consisting of two main categories, self-healing materials are either extrinsic or intrinsic. Extrinsic self-healing uses microcapsules or vascular networks embedded into the bulk of the material, which facilitate the introduction of either, a healing fluid, or a bacteria able to produce a like for like material at the damaged site (Hager, 2010; De Muynck, 2008). Whereas, Intrinsic self-healing materials have an innate self-repairing capability which occurs at a molecular level, and is activated by an external stimuli, such as heat, electrical or mechanical force (Hager, 2010; Blaiszik et al., 2010).

Showing these in more detail, Figure 1. illustrates how each of these mechanisms operate: Micro capsules (a), vascular networks (b) and intrinsic re-bonding of the material's molecular structure (c).

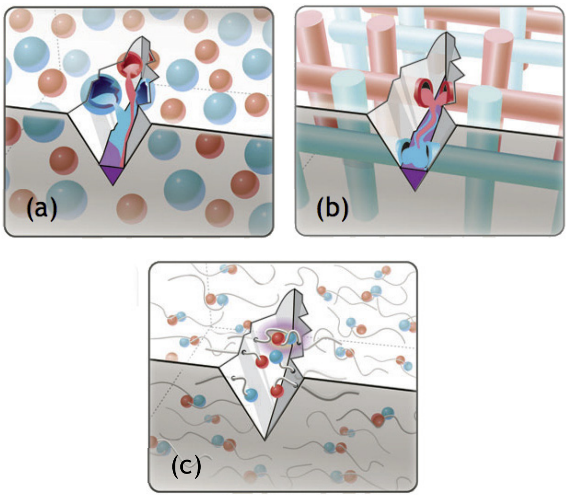


**Figure 1. Self-healing mechanisms: Extrinsic - microcapsules (a), vascular networks (b), and Intrinsic – reforming of molecular bonds (c). Extracted from Blaiszik et al., 2010.**

This technology has been explored within a range of materials, such as concrete (De Muynck, 2008; Sarkar et al., 2015) polymers (Gordon et al., 2017; Hia, Vahedi & Pasbakhsh, 2016; Mauldin & Kessler, 2010), metals (Ferguson et al., 2014; Ghosh, 2009) and glasses (Singh, 2014) to name a few. However, new material compositions are continually being proposed from within both academia and industry. Moreover, considering the functional benefits they might offer to the energy, construction and automotive sectors, the market for this technology is anticipated to continue to grow (Grand View Research, 2017).

Developed as either self-healing coatings or bulk materials, authors have proposed a number of potential applications that would benefit. These include aerospace (Das, 2016; Gordon et al., 2017), batteries and fuel cells (Wang et al., 2013), medical devices (Wang et al., 2016; Adaptive Surface Technologies, n.d), and consumer electronics (Blaiszik et al., 2012; Wu et al., 2017). Yet, few of these propositions have been tested beyond a laboratory setting, and there are only a handful that are currently commercially available. Of those available on the market, one of the more commonly discussed applications is self-healing paints, especially for the car industry to withstand day to day scratches (AutoScene, 2009; Nissan Motor Corporation, n.d). However, there are others that can be used in deep sea and military spaces as a method for preventing corrosion and increasing the overall integrity of the surface and structure (Automomic materials, n.d).

In regard to self-healing technologies that have been applied at a product level, consumers can now purchase self-healing bikes tires (Slime Products, 2019), car tires (Continental, n.d), self-healing gas tanks (HIT-USA, 2019), and self-healing jackets and bags (Imperial Motion, n.d). While each of these employ different types of self-healing, the variety of products that have utilised this technology indicate the potential market and industry that could exist for this innovation.

Since 'Virtually, all materials are susceptible to natural or artificial degradation and deteriorate with time' (Ghosh, 2009, p1), self-healing technology presents a unique opportunity to explore ideas relating to the lifetime extension of products. As, within a Circular Economy, one of central philosophies is to 'keep products, components and materials at their highest utility and value at all times' (Webster, 2015, p16), materials and products that can maintain their physical integrity for longer could assist in this endeavour.

Developed as part of the EPSRC funded research consortium 'Manufacturing Immortality', this paper examines how self-healing might relate to product lifetime extension, and addresses the question of *What are the benefits that self-healing might offer to product lifetime extension within Circular Economy contexts?*

## Methodology

To explore the research question defined above, firstly, a literature review and state of art of self-healing materials and product lifetime extension was conducted to locate and analyse where these two fields of enquiry might converge. Using the search engines Google Scholar and Scopus the following key words were used to define the literature considered 'Self-healing', 'Materials', 'Durability', 'Product Life-time Extension' and 'Circular Economy'. The results of this review process is presented the next section.

## Results and Discussion

### *Product Lifetime extension and self-repairing systems*

Product lifetime extension is defined as 'the postponement or reversal of the obsolescence of a product through deliberate intervention' (Bakker & Schuit, 2017, p.12) and it has been proposed as a central strategy for addressing and reducing the environmental burden of products (Allwood et al., 2011; Bakker et al., 2014; Ardent & Mathieux, 2014).

A product's life can be prolonged through a number of different approaches, such as reuse, maintenance, repair, and remanufacturing (Bocken et al., 2016; Nußhol, 2017). However, repair and maintenance has been proposed as a pertinent strategy, as it allows for a greater material efficiency (Stahel, 2013). By following the Inertia Principle, repairing practices replace or treat only the smallest part of the technical system, therefore allowing the highest economic value to be preserved (Stahel, 2010). So, if considering this in relation to self-healing, a technology that has the ability to maintain and self-repair itself in situ, without the need for human intervention or considerable resources, would most likely be considered highly advantageous from this perspective.

A viewpoint that has been initially explored by Akrivos et al., (2019), they proposed that self-healing systems would apply to the inner most loop of the technical cycle facilitating a practice of self-maintenance shown in Figure 2 below.

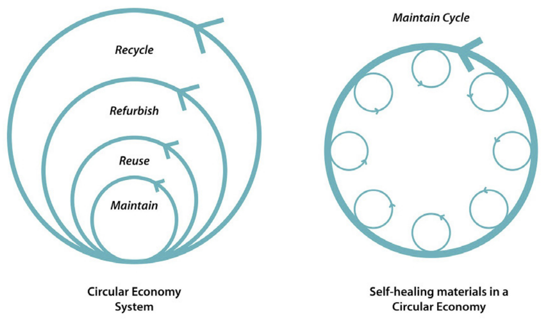


**Figure 2. Extract from Akrivos et al., (2019).**

Although only a preliminary supposition, it highlights the importance of a products primary lifetime in more detail. This is important as 'central to product life extension is the concept of a product's lifespan' (Bakker et al, 2014), which according to Cooper (2010), should be considered from two perspectives: the products technical life and the products service life.

The technical life of a product is defined as the 'maximum period during which it has the physical capacity to function' and the service life as the 'total period in use from initial acquisition to final disposal as waste' (Cooper, 2010, p9). While these distinctions describe two different viewpoints for how the lifetime of a product can be assessed, when considered in relation to self-healing materials, two opportunity spaces can be identified. Firstly, the structural and functional longevity, whereby the product or a part's mechanical properties are maintained, preserving its technical life. Secondly, the aesthetic functionality whereby the product is kept in service by preventing or repairing issues of wear and tear. These distinctions are explored in more detail below.

## *Extending the technical lifetime of a product*

The primary benefit that self-healing materials provides is the ability to enhance the physical integrity of the material, slowing down the aging of materials or parts (Aissa et al., 2012; Ghosh, 2009; Schlangen & Sangadji, 2013). While overall this would provide an improvement to the lifetime of the product or material, this could be particularly beneficial in scenarios where damage cannot be easily detected. Some materials such as concrete or asphalt can develop micro-cracks over time, which aside from being difficult to diagnose, affect the overall integrity and durability of a material increasing the risk of more catastrophic failure to occur later (Herbert & Li, 2013; Su et al., 2017).

The application of self-healing technology could also help to maintain the efficient operation of energy producing products. For example, wind turbine blades are often subjected to a great deal of external stresses affecting the overall efficiency of the machine (Yang, 2013). So, the integration of self-healing as a method of minimising costs of repair and to ensure an efficient long-lasting product is an area of significant interest (Fifo, Ryan & Basu, 2015).

Lastly, beyond reducing the overall environmental burden a product may have over its lifecycle, there are some situations where the application of self-healing materials also provides an added benefit by reducing the costs and the risks that can be associated with repair (Hager et al., 2012; Aissa et al., 2010). This is particularly important in circumstances in which repair is typically expensive or dangerous, as for example with medical implants or extreme environments. With medical devices such as pacemakers, the replacement or repair of devices can be both costly and at great risk to the human health (Costea et al., 2008). So applying self-healing materials where maintenance is not possible, such as prosthetic limbs and other implants would be highly beneficial (Hai, Vahedi & Pasbakhsh, 2016).

In summary, considering all the examples provided above regarding how self-healing applies to the technical lifetime, three key benefits were identified. These are that Self-Repairing systems provide: *Enhanced Physical Durability, Maintained Efficiency* and an *Increased Reliability* to products.

It is predicted that these factors would contribute to the extension of the technical lifetime of a product. This would benefit not only user by providing a product that is more durable and reliable, but also producers, who can provide longer lasting quality assurance, reducing the cost and risk associated with future repairs or replacement.

## *Extending the service lifetime of a product*

Aside from physical longevity, self-healing could also mitigate issues relating to emotional obsolescence and aesthetics. Wear and tear has been shown to be key determinants for why durable, functioning products are replaced by consumers (Van Nes & Cramer, 2005). While some researchers in the past have approached this issue by considering materials that can age with grace (Chapman, 2015; Bridgens et al., 2015), materials and surfaces that can be designed to withstand scratches and discolouration could also reduce this type of premature replacement. While it has been more commonly proposed for the automotive industry, there could be a significant advantages to applying these to 'shorter' living products, such as mobile phones, tablets and laptop computers. Furthermore, this also assists with the reuse and resale of objects, as it would help products retain their value for longer, and in turn stimulate the second hand market.

Another opportunity for extending the service lifetime is within the cycles of reuse and refurbish. Products such as broadband or TV boxes can operate in up to 5 different households in their lifespan. Throughout these lifetimes these products undergo wear which can result in the external casings needing replacement between each user (Teleplan, 2016). This practice causes both environmental and economical issues for the product refurbisher. Therefore, the application of self-healing coating could alleviate this situation, whereby the material would undergo a process of refurbishment and be returned to a like new condition.

In summary, contemplating the examples presented above one key benefit that self-healing offers was identified, which is that it provides an *Enhanced Aesthetic Resilience* to products. This factor is not only beneficial to users, but also remanufactures, demonstrating the wider value that this technology could provide for sustainability contexts.

In all, while there are some benefits that are more specific to the technical lifetime, and others the service lifetime, there are some that apply to both such as the *reduced cost and risk of future repair*. However, when considered together they represent the overall benefits to product lifetime extension. These have been consolidated into Figure 3, below to demonstrate how they relate to one another and the stakeholders they benefit.

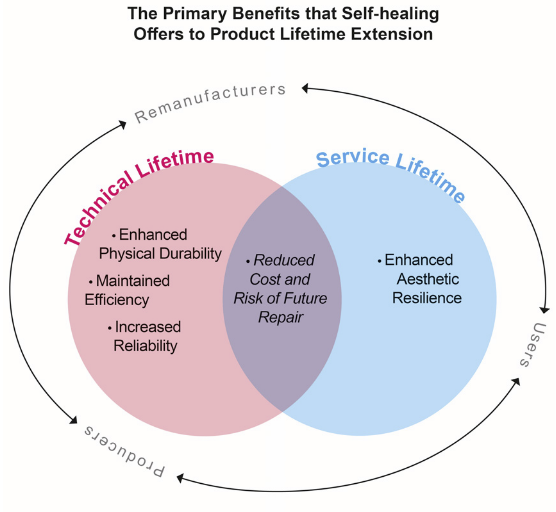


**Figure 3. Proposed benefits that self-healing might offer lifetime extension.**

## Limitations, challenges and future research

One key limitation of this field of research is that very few self-healing materials have been tested beyond the laboratory scale. Self-healing concrete is the first example of a material found in the literature to be tested in the field (Wiktor & Jonkers, 2016; Al-Tabbaa et al., 2019). There are however, several self-healing coatings available on the market, which would have undergone industrial testing and therefore ready for application. Future studies are required to test newly developed materials to advance this field of research and therefore confirm their ability to contribute to product lifetime extension.

Another limitation with self-healing systems is that while it has been demonstrated that healing can be effective on small scale damages, such as scratches and microcracks, self-healing of large scale damage has yet to be fully realised (White et al., 2014). Initial solutions include the introduction shape memory polymers to close larger cracks (Ferguson et al., 2014), and the integration of gel like substances that act as gap-filling scaffolds (White et al., 2014). However it must be understood that there may be some levels of damage that are beyond repair. This then would indicate that there must be careful consideration of the design application spaces for these materials, and a good understanding of the conditions that need to be created for the self-healing to occur.

One of the potential issues with self-healing materials within a Circular Economy context is the notion of persistence. Identified as a factor that must be deliberated when trying to understand the toxicological and eco-toxicological characteristics of how materials flow within the technosphere and biosphere (Braungart, McDonough & Bollinger, 2007), some materials persist within the natural system resulting in negative environmental impacts (Lindahl et al., 2014). So, materials that have the potential to reform bonds or integrate healing fluids in response to mechanical damage may present issues at end of life. Therefore, it is important to investigate, from a whole systems perspective, the potential rebound effects of adopting self-healing materials within industrial product systems.

## Conclusions

In conclusion, through literature review of self-healing technologies and product lifetime extension, five key benefits were identified. These relate to both extending the technical and service lifetime of a product. They are: *Enhanced Physical Durability*, *Maintained Efficiency*, *Increased Reliability, Enhanced Aesthetic Resilience and Reduced Cost and Risk of Future Repair.*

Lastly, in order to fully validate these factors identified, future research and field testing of these self-healing materials and coatings would need to be conducted, to uncover whether or not they positively contribute to the overall lifetime of products.

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