Prototyping Circular Materials Based on Reprogrammable Matter

Blaney, Adam*[a]; Richards, Daniel[b]; Gradinar, Adrian[b]; Stead, Michael[b]

[a] LICA, Lancaster, United Kingdom

[b] LICA, Lancaster, United Kingdom

* a.blaney@lancaster.ac.uk

For almost two centuries, design, manufacturing and consumption models have exploited Earth's valuable resources (elements, minerals, flora and fauna) on a profound scale. As resources become depleted, there is a desperate need to develop new approaches for how materials are utilised and fabricated with to reduce or even reverse waste and pollution. The research aims to create a new design and fabrication process that can develop circular materials, which contributes to a circular economy. The research presented documents initial prototyping explorations that build towards a vision of physical products/structures composed of reprogrammable matter. Meaning, an object's properties (shape, colour, texture) can be updated by uploading information from design tools into matter to avoid redundancies and heal damage. The research is presented as a pictorial in the format of an annotated portfolio that combines photographs and videos to communicate the research-through design process along with our findings and insights.

Keywords: Circular Materials; Reprogrammable Matter; Tuneable Environments

1 Introduction

Current design and manufacturing processes use huge amounts of energy, as well as producing significant waste and pollution in the process of converting raw materials into physical products and architectural structures. Typically, when products/structures break, become unfit for purpose, or are no longer needed they are dismantled or thrown away and disposed of – often in ways that damage our environment. Alternatively, imagine if the materials that make up our future products, structures or cities were not subject to these same linear cycles. What if, the materials of our future products and buildings were infinitely malleable and could be updated on-demand and/or in response to specific stimuli. This would enable physical products to self-heal when damaged and evolve over time in response to user needs. Such material properties would provide a wide range of possibilities for product innovation whilst simultaneously helping us tackle key challenges associated with sustainable production and disposal of physical products.

This pictorial presents initial explorations into developing an object (an earing) composed of materials that can be updated on-demand and at high resolutions. This is done by developing a novel design and fabrication approach based on interrelationships, which can maintain a discourse with a structure's material make-up, design parameters, and stimuli. This approach is termed tuneable environments (see figure 1). Tuneable environments rethink and provide an alternative approach to 'programmable matter' it also incorporates principles of 'Persistent Modelling' (Ayres, 2012). This is because the general approach to programming matter, in a design context, have been developed by pre-designing the geometry, and interfaces of individual material units and then supplying them with random external energy/stimuli (e.g. fluid agitation) (Tibbits, 2016). This has produced structures that can autonomously assemble and also reconfigure their geometric shapes, which have recursive properties (Tibbits, 2014). Importantly, Persistent Modelling establishes how a discourse between design representations and physical structures, post-fabrication, can be maintained by using parameters of associative design models to modulate parameters of stimuli (water pressure) that deform both the digital and physical shape of a structure (Ayres, 2011). Tuneable environments is based on the idea of modulating parameters of energy/stimuli (e.g. heat, magnetism), via digital design tool parameters, as the means to programme matter (Aurthor, 2020).

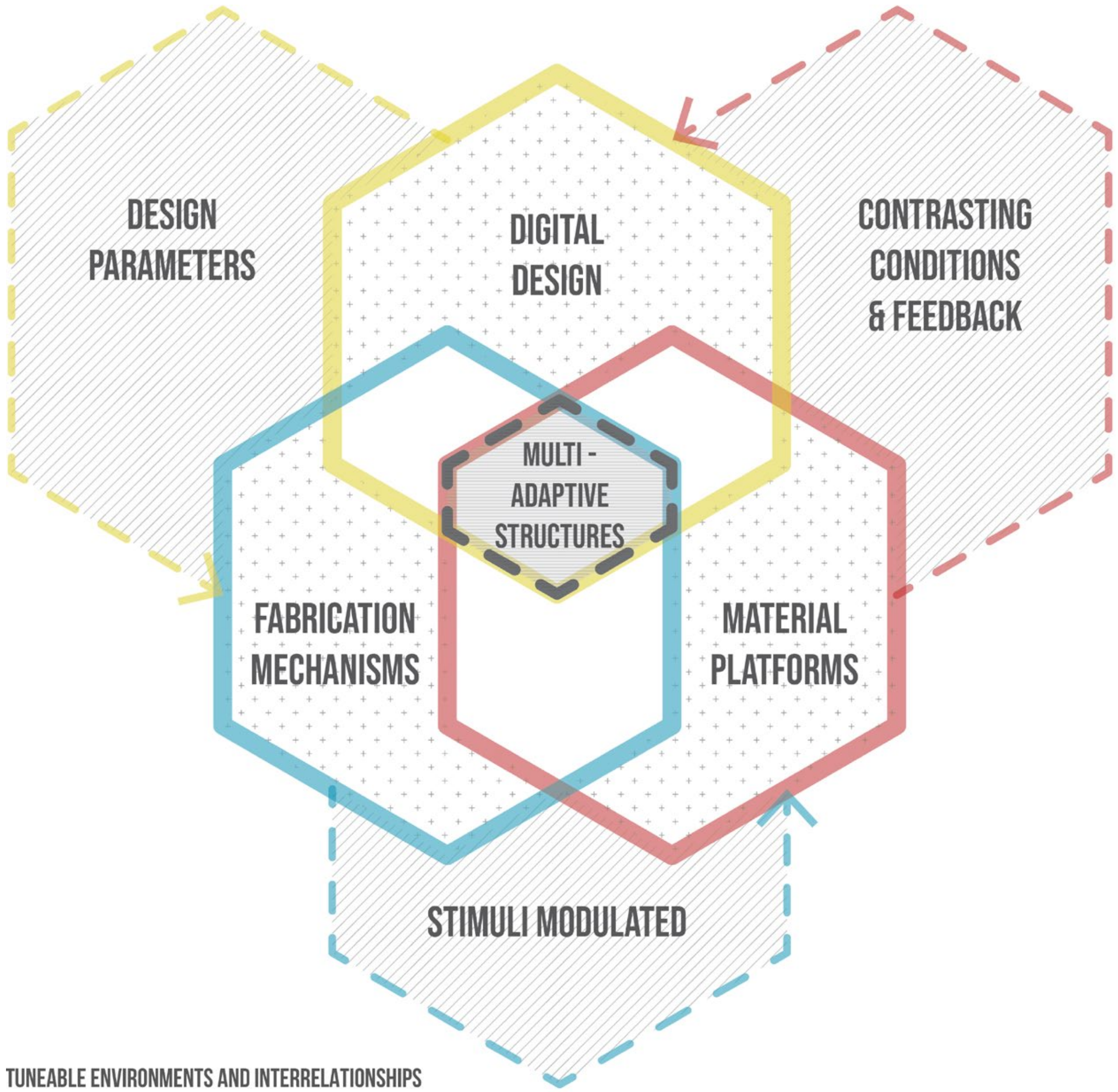


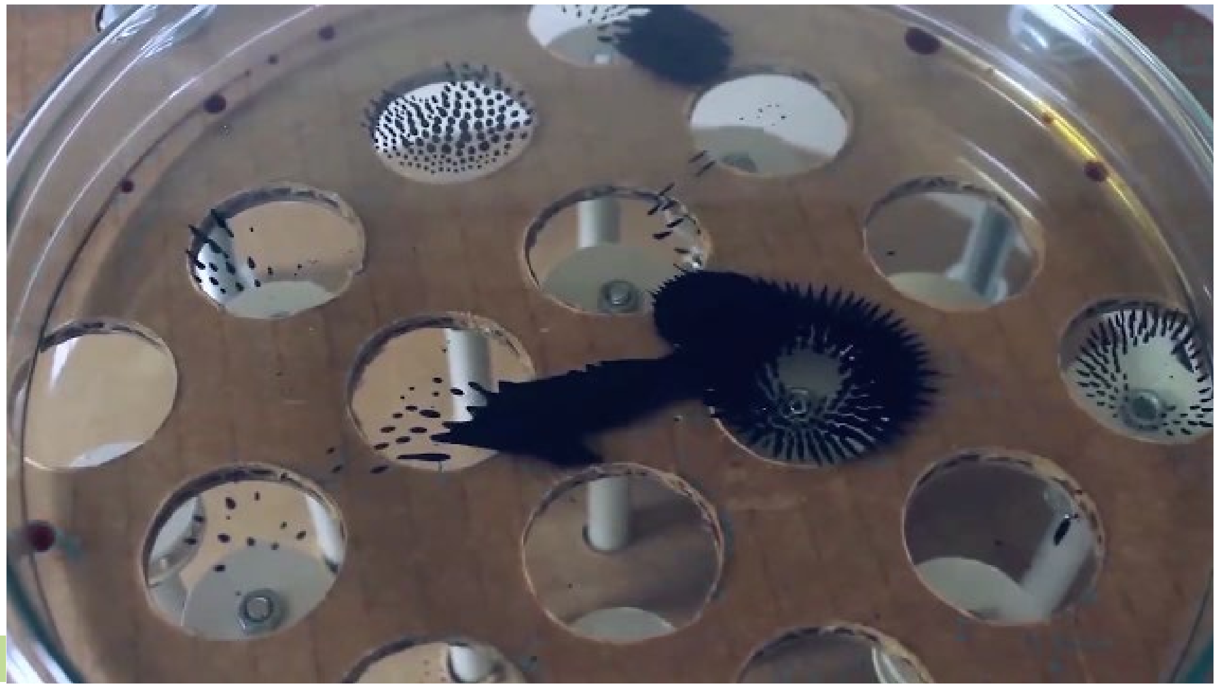
Figure 1. Tuneable environments is a design and fabrication approach based on interrelationships, which highlights the potentials of circular materials.

An ongoing challenge within programmable matter and responsive architecture centres around the ability to 'update' and create radically different shapes/formations and material attributes (colour, compositions, textures etc) at finer-grained resolutions, which would enable increased flexibility and more customised/sensitive responses i.e. the ability to reprogramme and update matter on demand. In doing so, these increased material abilities would highlight a move towards circular materials, which could contribute towards ideas of a circular economy based on modular parts that can be updated interchanged between products (Stahel, 2001). A popular fictional vision of sophisticated matter that can be reprogrammed is depicted in the 1991 film "Terminator 2" with the T1000 robot capable of changing its shape, surface texture, colour as well as self-heal at will. Leveraging structures with such abilities could begin to significantly reduce associated waste (material, financial, land) and pollution that can be attributed to linear design and fabrication processes and modes of consumption that predominate. The key question that the practical material explorations documented in this pictorial have sought to address is: if we could collect and understand data related to a product's usage in the wild, would it be possible to push physical updates into real-world products composed of reprogrammable materials? What would be the technical and methodological challenges? How would this require designers to rethink their workflows? How might such a capacity impact sustainability and contribute to aspects of a circular economy?

We now present our initial explorations and developments for creating a reprogrammable earing. These explorations are guided by this vision of developing matter that can be updated via stimuli as a means to interact with materials at high resolutions. This guiding aim is further facilitated by employing Research Through Design as a flexible and iterative approach (Gaver, 2012). The initial developments are documented using multiple videos and photographs in the format of an annotated portfolio. Bowers discusses that the artefacts generated from RtD embody design thinking that is highly 'varied, multi-faceted, heterogeneous', which can be documented and unpacked through the use of annotated portfolios (Bowers, 2012). The main reason for incorporating videos is that they further demonstrate the dynamic (shape-changing and self-healing) qualities of the materials as they are being reprogrammed. Additionally, photographs with annotations are used to highlight: 1) the areas of interest being explored in subsequent iterations. And 2) the static nature of photographs compared to videos, highlight the ability to temporarily freeze design updates into materials and hold them by hand when using multiple stimuli and state-changing material.

Initial stages: 2D fluid patterns & real-time manipulations

Video



Video 1. Documents a preliminary prototype set-up, where 2D ferrofluid patterns are manipluated in real-time by moving multiple magnet controlled via digital design tool.

Figure 2. Illustrates the various array of global patterns and the localised formations of the ferrofluid generated when it is manipulated by varying the stimuli of magnetism.

Uploading digital information into matter: limitations of fluid materials

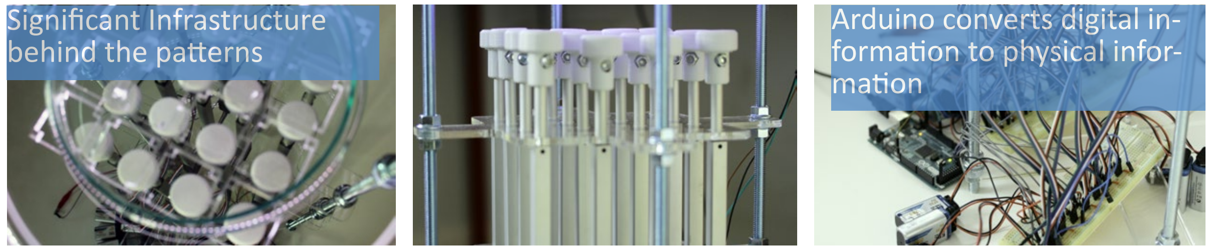
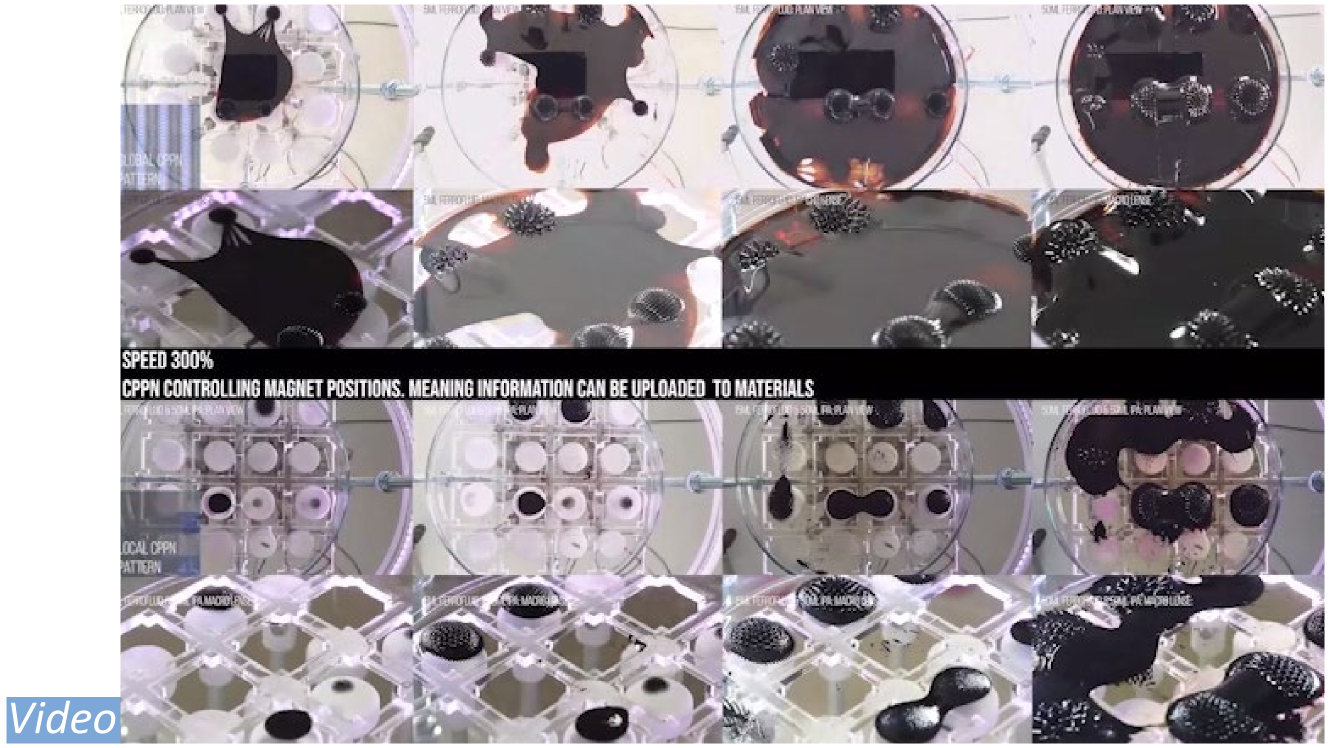


Figure 3. Higlights the infrastructure behind the 2nd iteration of the prototype set-up. Importantly, an Arduino allows us to send instructions from a design tool and modulate parameters of stimuli (magnitude, location, duration). The glass tank is 190mm in diameter. The 4x4 grid of magnets is at 45mm centres. Each magnet is 20 x 10ml and has a 14.8kg pull



Video 2. Compares various global and local ferrofluid patterns generated with increasing volumes of: 1) only ferrofluid and 2) ferrofluid combined with 50ml of Isopropyl alcohol. Volumes between 5 - 15ml produced clear pattern formations. This reveals challenges of scale based on the amount/resolution of information that can be 'clearly' uploaded into increasing sizes/volumes of material, which may be overcome by introducing scaffold structures.

Figure 4. There are several main challenges of interest with ferrofluid at this point: Firstly, the ferrofluid can not be taken out of the tank and handheld. Secondly, the scalability and resolution of the data uploaded into the materials reach a limit. Thirdly, the patterns are arbitrary and the properties generated have no relevance to any design demands. These first two challenges will be further investigated by developing a multi-stimuli system and incorporating a state-changing material.

Using multiple stimuli to upload & temporarily freeze information into matter

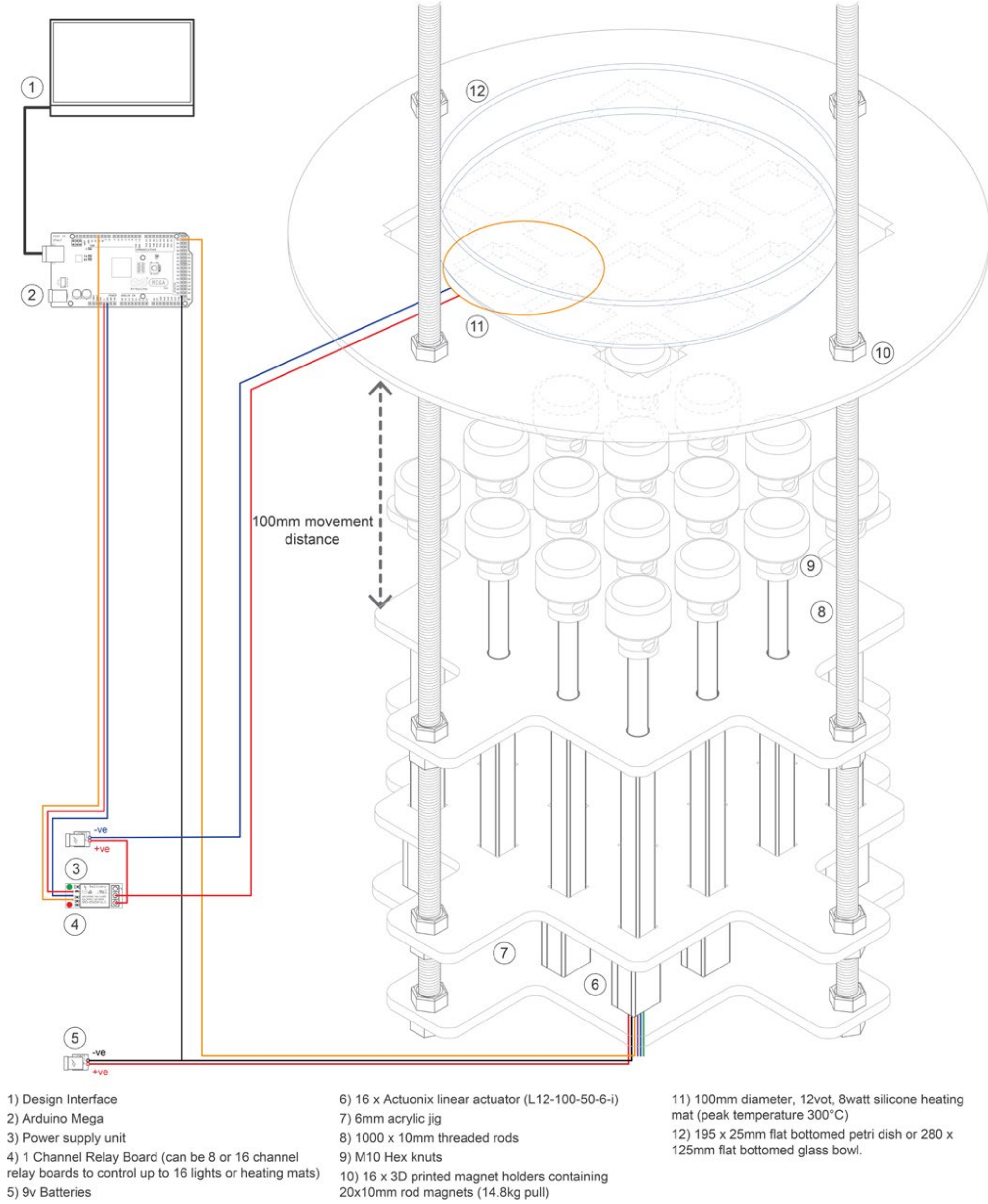


Figure 5. System diagram of the current prototype systemof a multi-stimuli system. The additional stimulus incorporated is heat, which is also controlled via a digital interface. The intention is to use heat to change a material from solid to liquid so strcutures can be updated and self-heald but also enable updates to be temporarily frozen in time so they can be taken out of the tank and hand held.

Self-healing: combing state-chaning & magnetic materials

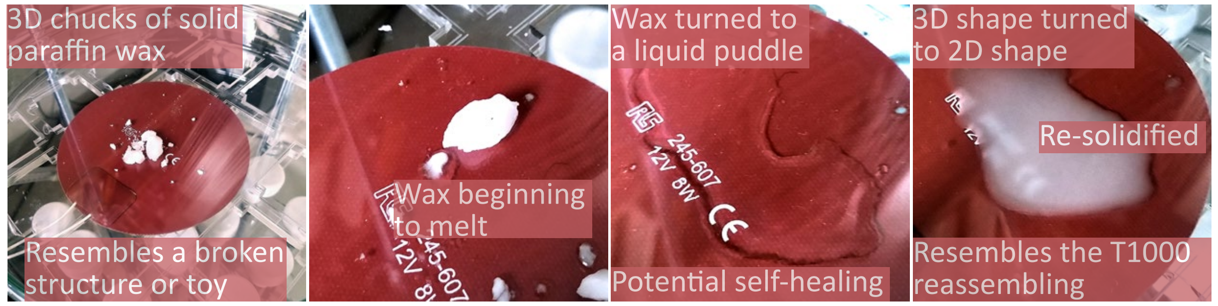


Figure 6. Series of images revealing paraffin wax changing state from solid to liquid and back again. The wax needs to be 'magnetised' so it can be manipulated by modulating magnetic stimuli. Importantly, the images highlights the potentials of developing a muli-stimuli system along with state-chaning materials.

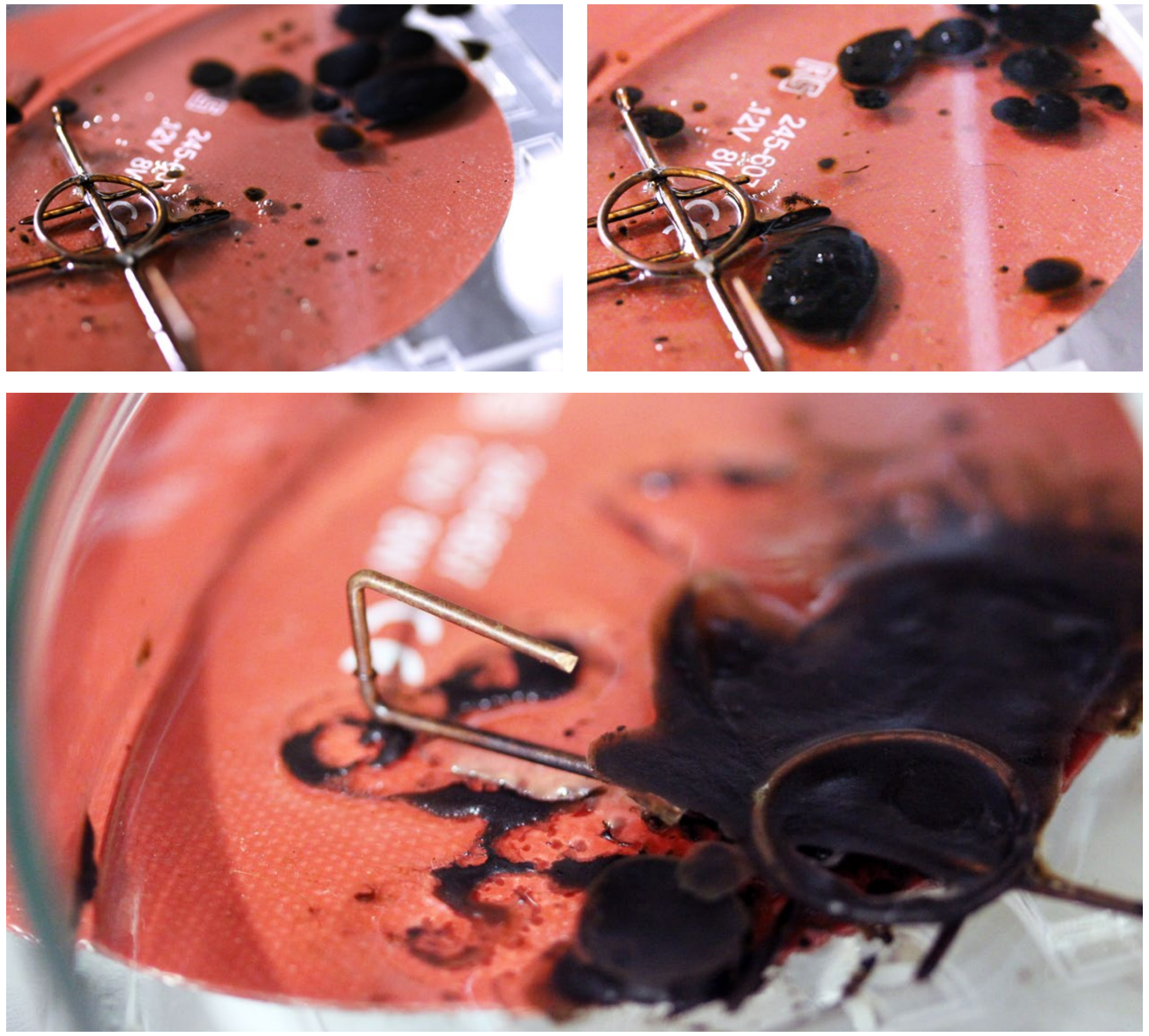
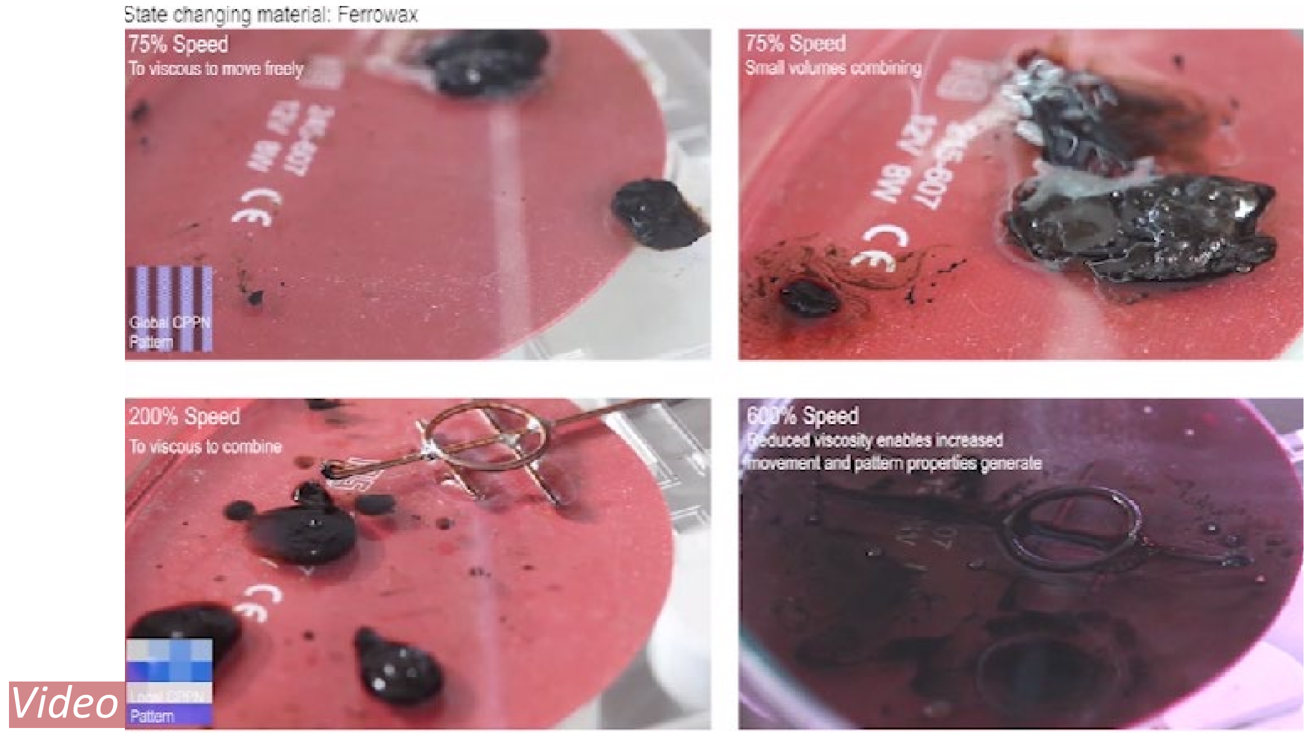


Figure 7. Taking inspiration from Raj et al (2001) and Oh et al (2005), the parraffin wax is combined with ferrofluid. As a result, the use of heat and the array of magnets enables the ferro-wax to be meleted and then manipulated via the magnets to create arbitrary patterns. A copper scaffold (non-magnetic) in the shape of a earing is used to provide some structure to the ferro-wax. Significantly, the initial explorations reveal the abilitity to repgroamme matter using a multi-stimuli system and state changing materials.

Handheld: pulling reprogrammable structures out of their tanks



Video 3. The video highlights the difficulties of manipulating the materials when it is in more of a viscous state and appear to only enable globules of ferro-wax to be manipulated to any significant amount. Hot water was added to reduce the ferro-wax viscosity but results in the volumes floating and producing more 2D like shapes. Importantly, the video reveals how state-changing materials can be manipulated at various stages and have information uploaded and temporarily frozen into them.

Figure 8. Is a first final state of an earing structure that can have it's materials reprgrogrammed aprart from the copper wire scaffold. The photographs reveal complex and varried: patterns, thicknesses, textures and translucencies.

Repairing and reprogramming structures with varied, high-resolution patterns

Video 4. Documents a 2nd and 3rd ferro-wax structure. The 2nd iteration documents increasingly varied shapes and material distributions as well as homogenous colours. The 3rd iteration demonstrates self-healing abilities as well as multiple colours and material gradients.

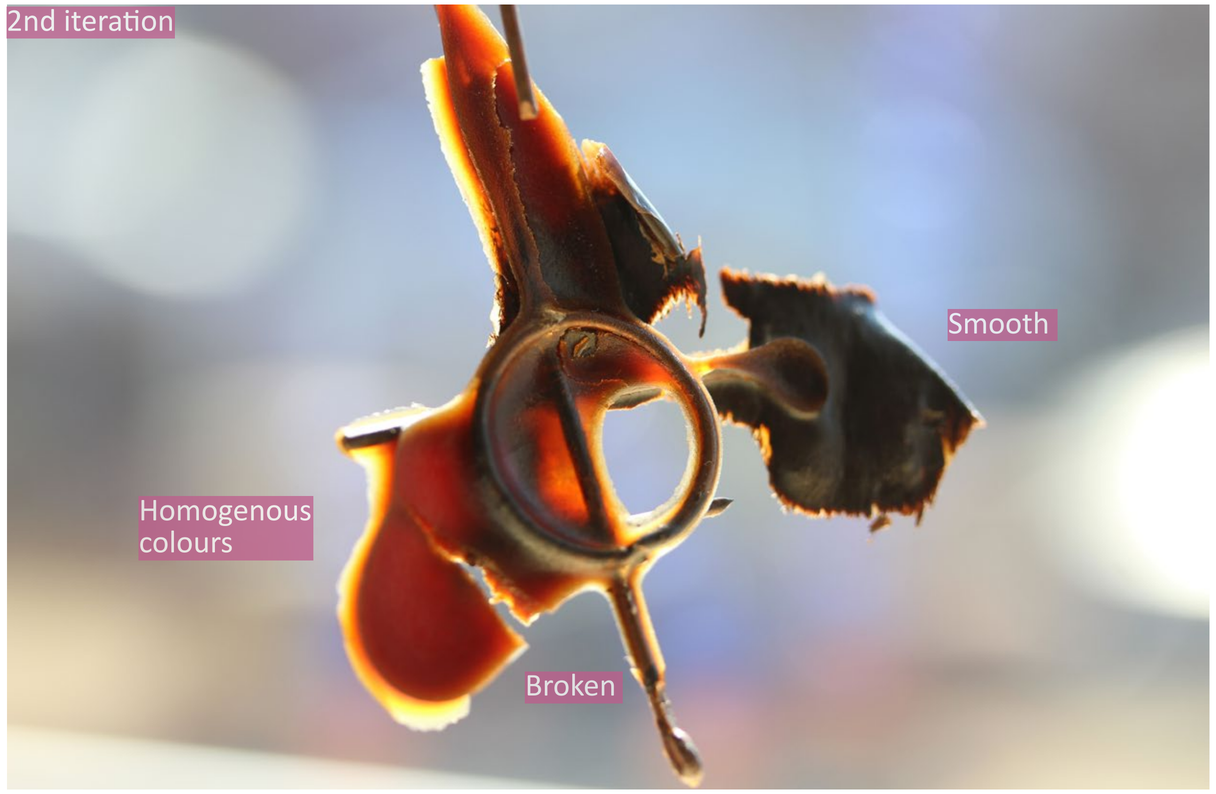


Figure 9. Documents the 2nd iterations of the earing, which has generally smooth textures and a homogenous colour. This iteration was also slightly broken when removing it from the taken as the wax stuck to the glass.

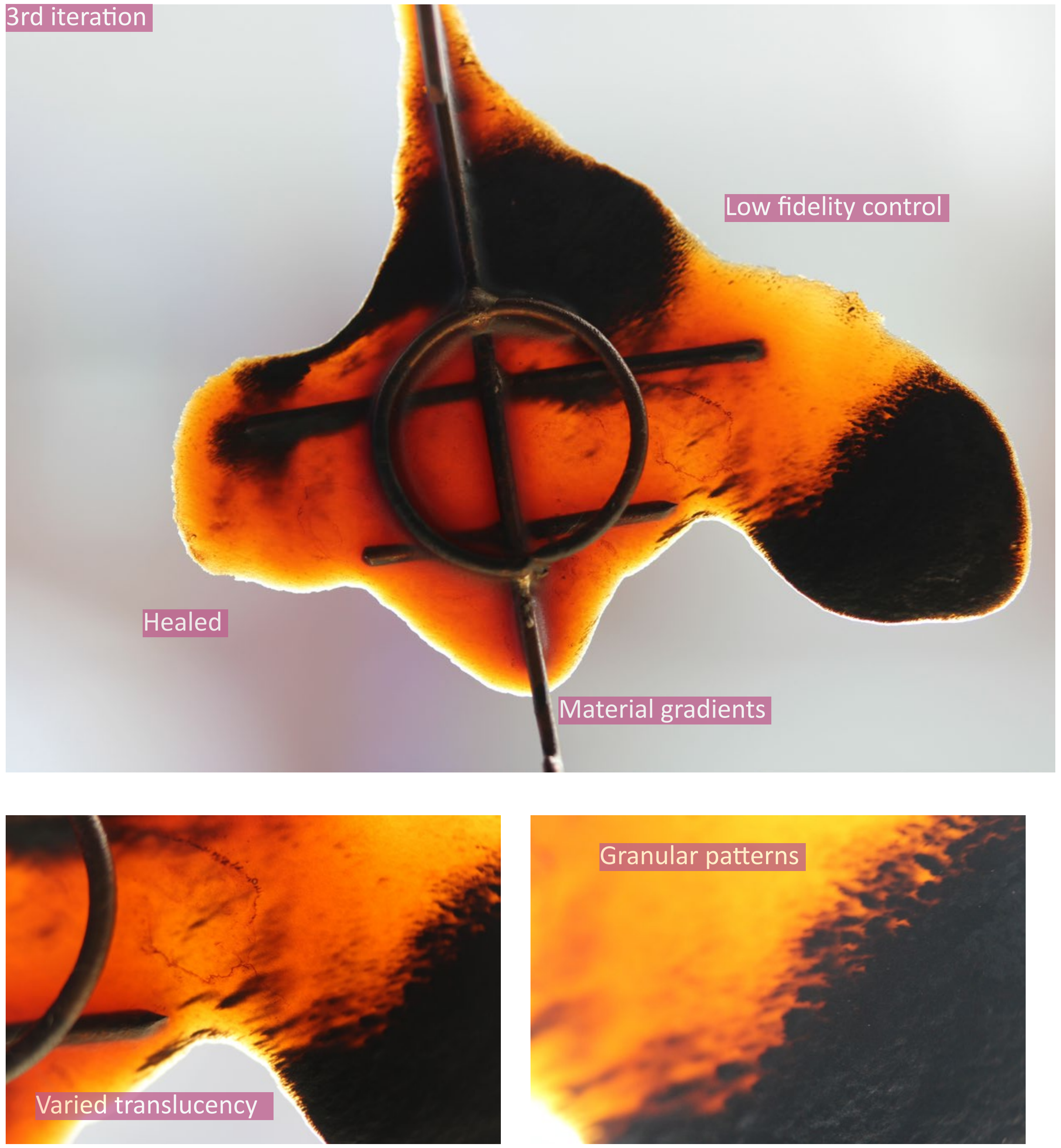


Figure 10. Documents the 3rd iterations of the earing. The material was self-healed when melted and various complex gradients, colours and patters were produced. This highlights the potential of creating circular materials that can be repgoramméd at high resolutions using tuneable evironments as a design and fabrication approach. However, control over these properties is limited as there is no feedback and the properties are not informed by specific design demands/associations.

Discussion

The work has sought to explore how future products could be designed with multiple physical attributes (e.g. shape, texture, colour) such that they can be updated on-demand in response to physical stimuli. In doing so, we have demonstrated that such material capacities can be achieved, with limited fidelity and control, and we suggest that this illustrates exciting opportunities for design and development of matter that can be reprogrammed, which demonstrate circular material abilities. Circular materials could contribute to the circular economy agenda by addressing issues of material waste and pollution as products can have their matter reprogrammed/updated. However, as mentioned, there are challenges of misuse if updates can not be temporarily frozen into a product's matter.

This pictorial has documented our material investigations with ferrofluid and wax in the form of an annotated portfolio. The annotations and combinations of videos and photographs help to document: 1) the design thinking as the prototype is developed into a multi-stimuli system that incorporates state-changing materials. 2) Material challenges that impact the resolution and types of material properties generated in each iteration (e.g. viscosities). 3) Material abilities, both static ('freezing' updates) and dynamic (self-healing and shape-changing) of each iteration enabled through RtD. Where RtD further enabled the iterative development guided by an overall aim to reprogramme matter, which raises new insights and potentials.

Our prototype creates what we term a circular material, which is made possible as a novel design and fabrication process has been developed, which we term as tuneable environments. Importantly, our tuneable environments approach enables interrelationships between design with material properties as well as new material interactions at high resolutions. As a result, it highlights an alternative for circular economies, which can be based on costly and energy-intensive recycling processes to maintain and repurpose/remanufacture material resources. Through these material iterations, two main insights and multiple future challenges for designers have been uncovered.

1.1 Insights: Reprogrammable matter

The main insight from this research is the ability to upload and temporarily freeze design information into a product's material make-up at high resolutions. This addresses potential issues of misuse that could arise within reprogrammable matter/circular materials. The ability to temporarily freeze information into matter is only possible by developing a multi-stimuli system that combines heat and magnetism, building upon our previous research (Blaney, 2020), and also, incorporating state-changing materials (ferro-wax) that can only be updated/manipulated in a liquid state by a second stimulus. It also appears that the ability to switch materials into a liquid state enables complex and high-resolution material properties, such as material gradients, translucencies, textures, global shape changes and complete self-healing. Finally, in regards to circular economies, the state-changing materials allow objects to be taken out of a tank and held but also placed back in their fabrication environment and re-updated based on these interactions. As a result, a distributed network of remanufacturing that can occur in peoples homes instead of transporting materials to centralised recycling plants could be possible. Furthermore, the ability to physically interact and iteratively update these materials could open up the possibilities to capture unique interactions, which could generate highly bespoke products that do not become redundant. Unlike current linear design, fabrication and consumption processes that contribute to the current issues of a make, use, dispose.

By using stimuli to programme matter, it extends the material properties/palettes available to designers, which could bring about new application areas for reprogrammable matter and new human-product interactions may become possible. For example, imagine medical prosthetics that can be grown around a patient's limb and as they grow or their body composition changes. The ability to reprogramme multiple material properties of their prosthetic by placing it back into their own fabrication tank overnight as they sleep, and waking up to a newly configured prosthetic could significantly improve comfort and functionality. Additionally, material waste and inefficiencies (transportation, degradation, separation) could be significantly reduced in this process, opening up opportunities to rethink design and fabrication of further products to reduced our environmental impact. All of which could further contribute to aspects of a circular economy related to manufacturing and material resources. Imagine taking a child's old clothes and trainers that are damaged and no longer fit them to a store and having them all melted down and updated to a new size with an infinite number of patterns and colours available to create new designs. These discarded clothes would not have to go into landfill, which produces toxic waste (EDGExpo, Fletcher, 2008, WRAP, 2020).

Reflecting on the prototypes, material abilities achieved and proposing potential applications based on these novel abilities, various challenges become apparent that will inform future explorations.

1.2 Challenges

There are several key challenges for future work:

1. **Scaffolds**: The 2D ferrofluid patterns were highly flexible and reprogrammable. This was achieved by moving the magnets under the petri-dish up and down using linear actuators. The copper wire in the shape of an earring acts as a rigid scaffold and this limits the extent the ferro-wax can be manipulated. Future research will explore various fabric scaffolds in order to create adaptive sportswear that can have multiple properties updated based on sensor data (temperature), which could aid performance or enable highly customised garments bespoke to any athletes needs. For example, the clothes for cyclists do not change properties irrespective of weather conditions, exertions or injury. Imagine a cycling top that becomes more open as the cyclist become hotter to prevent overheating. Or, changes surface texture at various stages on the course (descents, sprints, time trials) to reduce 'drag'. Or, self-heals and supports a cyclist if there has been a crash. This would mean less equipment is needed for multiple riders in a team across a season.

2. **Infrastructure**: The infrastructure (i.e. linear actuators and magnet setup) required to induce stimuli (material actuation) and upload information into materials so they can be reprogrammed is quite significant and cumbersome. As a result, real-world application whereby materials can adapt in near real-time and in place/in-situ is currently limited. What is required for this approach to open up applications is the ability to embedded sensing and actuation into our state-changing materials that do not restrict material resolutions/flexibility. An issue that pre-programmed and responsive approaches address (Scott, 2018).

3. **Feedback and design intent**: The current work has focused on developing a prototyping platform to control adaptive materials. However, the patterns and ear-ring forms produced are currently relatively arbitrary and non-functional. To address this challenge, two key elements require further research and consideration. (a) how can we integrate sensing capacities into the materials or scaffolds such that material adaptations can respond to real-world demands? (b) how can we identify what, and to whom a "desirable" material adaptation would be in various application domains? Notably, we suggest that design fiction may provide a useful mechanism for exploring these questions as a means to fuel future prototyping.

4. **Resolution**: The resolution of patterns and forms produced by the ferro-wax were impacted by two elements. Firstly, different volumes of ferrofluid influence the ability of the magnets to create specific patterns and move materials around. Secondly, the resolution of the magnet grid also impacts the resolution of the image patterns in our experiments, in much the same way the resolution of an image shown on a digital display is impacted by the number of pixels in the digital display. Further research is required to understand the scalability and threshold of material resolution within various applications.

5. **Material palettes:** The material palette afforded by the ferro-wax is still limited in terms of application for physical products. Namely, colours, rigidities and complexity of form. Interdisciplinary

collaborations with chemists and material scientists are required to overcome and develop new material palettes that afford designers possibilities for designing and deploying reprogrammable materials in future products.

Acknowledgements. These initial investigations formed the basis of a feasibility study project (Developing the future of adaptive materials based on HD-reprogrammable matter), which has been funded by Connected Everything II (EP/S036113/1).

2 References

Blaney, A., 2020. Designing Parametric Matter: Exploring Adaptive Self-Assembly Through Tuneable Environments. Lancaster University (United Kingdom).
Bowers, J. The logic of annotated portfolios: communicating the value of'research through design'. Designing Interactive Systems Conference, 2012 Newcastle, UK. ACM, pp.68-77.
EDGEXPO. Fashion Industry Waste Statistics [Online]. Available: https://edgexpo.com/fashion-industry-waste-statistics/ [Accessed 18 Feb 2021].
Fletcher, K. 2008. Sustainable Fashion and Textiles: Design Journeys, London, Earthscan.
Gaver, W. What should we expect from research through design? In: Konstan, J., A., ed. SIGCHI conference on human factors in computing systems May 2012 Austin, Texas, USA. ACM, pp.937-946.
Oh, K. W., Kak, N. & Chinsung, P. 2005. A phase change microvalve using a meltable magnetic material: ferro-wax. 9th International Conference on Miniaturized Systems for Chemistry and Life Sciences.
Raj, M. K. & Lennon, J. 2001. Ferrofluid sculpting apparatus. USA patent application.
Riesener, M., Schuh, G., Dölle, C. and Tönnes, C., 2019. The digital shadow as enabler for data analytics in product life cycle management. Procedia CIRP, 80, pp.729-734.
Stahel, W. R. 2001. From 'design for environment' to 'designing sustainable solutions'. In: Tolba, M. K. (ed.) Our Fragile World: Challenges and Opportunities for Sustainable Development. EOLSS Publications.
Scott, J. Responsive Knit: the evolution of a programmable material system. In: STORNI, C., Leahy, K., McMahon, M., Bohemia, E., and Lloyd, P, ed. DRS 2018: Design as a catalyst for change, 2018 Limerick, Ireland. pp.1800-1811.
Stahel, W. R. 2016. The Circular Economy. 531. Available: https://www.nature.com/news/the-circular-economy-1.19594 [Accessed 21/02/2021].
Star, S. L. & Griesemer, J. R. 1989. Institutional ecology,translations' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. Social studies of science, 19, pp.387-420.
Tibbits, S. 2014. Fluid Crystallization: Hierarchical Self-Organization. In: Gramazio, F., Kohler, M. & Langenberg, S. (eds.) FABRICATE 2014: Negotiating Design & Making. UCL Press.
Tibbits, S. 2016. Self-Assembly Lab: Experiments in Programming Matter, Routledge.
WRAP. 2020. Textiles [Online]. Available: https://wrap.org.uk/resources/guide/textiles [Accessed 18th Feb 2021].