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Design for Terra-Reforming: Prototyping Environmentally Responsible Socio-technical Futures

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Abstract:
From the *Gutenberg Press* to the *Internet of Things*, socio-technical progress has benefitted humanity in ways our ancestors likely never thought possible. Many advancements have, however, had a profoundly detrimental effect upon our planet's natural environment. Despite the growing spectre of climate change, technological systems continue to be designed and adopted with little culpability. We respond to these issues by outlining the foundations for a novel research approach – *Design for Terra-Reforming* (DfT) – which seeks to emphasise the environmental consequences that accompany socio-technical development as well as to help make such impacts more accountable. Reflecting on an initial case study, we discuss how DfT combines the actionable insights of *physical prototyping* with the future-focussed envisioning of *Design Fiction prototyping*. We then posit how DfT might be further developed into a critical framework for better sustainable governance of the threats future technologies may pose to Earth's climate and ecology.

Keywords: Sustainable futures; Terra-Reforming; Prototyping; Philosophy of Technology

1. Introduction

Technology is not, in and of itself, malevolent. Healthcare, communication and architectural technologies have been largely beneficial to humanity. However, many socio-technical advancements have also had a profoundly detrimental effect upon our planet's natural environment. Despite the growing spectre of the climate change, socio-technical processes, devices and systems continue to be designed and adopted with little culpability on behalf of their developers. Even innovations specifically intended to support planetary sustainability like recycling, solar power and energy monitoring, have been shown to be, at times, inefficient and resource intensive in their own right (Bishop et al, 2020; Mulvaney, 2014; Strengers, 2013). Kolbert (2021) notes this paradox by describing efforts to implement sustainable technologies as *'people trying to solve problems created by people trying to solve problems.'*

To begin to respond to and raise awareness of these issues amongst designers and technologists, in this positional paper we outline the foundations for a novel research approach – *Design for Terra-Reforming* (DfT). Through an exploratory case study which investigates the potential for a new *circular material* fabrication process, we discuss how we combined the actionable insights of *physical prototyping* with the future-focussed envisioning of *Design Fiction prototyping* to form our DfT approach. We then posit five themes for developing DfT into a more robust critical framework. Crucially, although nascent, we posit DfT could have the potential to help mindful technology companies explore the sustainable parameters of their emerging technologies and perhaps even aid policymakers in responsibly transitioning societies to circular economies as well as meeting Net Zero 2050 targets (Global Climate Action, 2020).

2. A Brief History of Earth-shaping

The environmental and ethical issues stemming from much socio-technological progress are keenly reflected in the concept of *terraforming*. The etymology of the term is rooted in Latin – a combination of the word *terra* which means 'Earth' or 'land' and the gerund 'forming' which is derived from the Latin *fōrma* meaning 'to shape.' The term thusly translates as *Earth-shaping*. Having originated within the science fiction genre, the concept provides the foundation for a growing area of real-world technological development sometimes also referred to as *Geo-engineering*.

2.1 A Fictional Foundation

The science fiction writer Jack Williamson (under the pseudonym 'Will Stewart') first coined the term *terraforming* in his short-story *Collision Orbit* (1942), where he describes a fictional alien planet *Obania* as '*smaller… less than a tenth the mass. There's plenty of time to land a terraforming crew, to install a new-type directional drive.*' With this passage, Williamson established the basic mechanics for the way in which the *terraforming* concept has continued to be applied across science fiction media and beyond. In essence, *terraforming* centres on how an innovative form of technology can be employed to directly alter the environment of a planet with the purpose of making it more habitable – '*especially so that it is more like Earth and could therefore be a place where humans could live'* (Dictionary.Cambridge.org, n.d.).

As Pak (2016) explains, such socio-technical visions have included modifying the '*climate, atmosphere, topology, and ecology'* of the world(s) in question. Using the much-debated *Gaia Hypothesis* as its through-line, Lovelock & Allaby's *The Greening of Mars* (1984) provides a compelling vision for *terraforming*. Lovelock's (1979) hypothesis posits that Earth's biological entities (microbes to homo-sapiens and everything in between) are interdependent and form a highly complex superorganism that must work together to regulate planetary conditions for all-natural life. As such, the book's story of humans' exploiting technologies to colonise Mars serves as an allegory for the formation of planets and biospheric life.

2.2 New Socio-technical Frontiers

Renowned astronomer Carl Sagan (1961; 1973) and NASA engineer James Oberg (1981) were early proponents of conducting real-world terraforming activities. Later, the physicist and geologist Fogg (1995) argued for distinctions to be made between the term *terraforming* – which he defines as using technologies to 'enhance' an *extra-terrestrial* planet to support human life – and *Geo-engineering* – in his view technological interventions specifically designed to alter Earth. Despite Fogg's demarcation, the terms have continued to be used interchangeably.

More recently, Kolbert (2021) has sought to determine whether it is actually possible to *reverse geo-engineer* Earth. Meeting physicists prototyping techniques to blast diamonds into the stratosphere to reduce global temperatures – a process that would turn areas of sky from blue to white – she surmises that it is often easier '*to ruin an ecosystem than to run one.*' Bratton (2019), working at the intersection between design and architecture, takes a more techno-utopian stance. He has appropriated the term *The Terraforming* to describe both the centuries of environmental degradation of Earth caused by humanity and what he sees as its remediation – a 'planetary design initiative' based upon advanced technologies alongside new policies and practices.

The concept has reached a wider audience through the rhetoric of the technology entrepreneur Elon Musk. Citing human-made climate change as a key rationale (Piper, 2018), Musk plans to use his *Space X* technologies to pioneer terraforming techniques on the Red Planet (Figure 1). Whilst such remarks could easily be dismissed as hyperbole, we argue that due to the pervasiveness and popularity of their innovations, technocrats like Musk, *Amazon* founder Jeff Bezos (Pandey, 2020) and *Microsoft's* Bill Gates (Gates, 2021) hold much power when it comes to influencing public perceptions of technologies as 'solutions' to Earth's climate crisis. Indeed, in recent years, major tech figures have regularly made environmentally conscious promulgations seemingly in order to divert public attention from the unsustainable impacts of their ubiquitous technologies (Stead et al, 2020; Milman & Rushe, 2021).

Figure 1. Terraforming related tweets by Space X CEO Elon Musk. Image credit: Twitter. (2021).

3. Design for Terra-Reforming

With the concept of *terraforming* gaining renewed traction as a research domain, we argue that we must begin to challenge the anthropogenic narratives which drive it, as well as socio-technical determinism more widely. Firstly, rather than looking to shape, and likely exploit, other worlds, humanity must urgently try to ameliorate the environmental problems presently faced here on Earth. We are already experts in maltreating a planetary environment – *our own*. Anthropocentrism is making the planet *less inhabitable*. We therefore argue that we must begin to sustainably *reshape* Earth's future as opposed to continuing to shape its demise. Secondly, if new technological processes, devices and systems are to be developed, we must do this with a newfound 'sustainable foresight' which critically evaluates the environmental impacts said technologies may cause – even if they are intended to support planetary sustainability.

We contend our DfT approach begins to respond to these issues. It is rooted upon a *constructionist-based Research through Design* (RtD) (Frayling, 1993; Gaver 2012) methodology. Gradinar (2018) describes RtD as a means for generating knowledge through 'the union between making and thinking.' Through RtD, researchers can create prototypes that help them to better understand the complexities of engagements with materials and the act of *designing* itself (Findeli, 2004; Ramirez, 2009). To both exemplify the beginnings of DfT and demonstrate its intent, we conducted an initial exploratory case study which centres on understanding the possible sustainable implications that may come with designing and adopting a new material ecosystem.

3.1 A DfT Case Study

Our long-standing, *linear* relationships with physical materials play a key role in terraforming the Earth's quietus. Many of the products we use and the environments we have created are composed of matter which is either finite, such as metals and minerals, or non-biodegradable and difficult to recycle, such as plastics (Weetman, 2016). The UK for example, consumes five million tonnes of plastic annually, yet only 7% of this material is recycled each year (UK Parliament, 2020). Additionally, around 1.6 million tonnes of electronic waste (e-waste) – comprised primarily of plastic and metals – reaches UK landfills every year (Forti et al, 2020). Calls to transition to a material culture which is built upon *circular* principles and processes have consequently grown louder and louder in recent years (Stahel, 2016; Ellen MacArthur Foundation, 2021). *But what type of new physical matter could, and indeed should, be developed to enable this circular epoch?* Matter with self-healing properties (Akrivos et al, 2019) and building materials that are cultivated from fungi (Goidea et al, 2020) are examples of bleeding edge research projects which are exploring the opportunities and challenges of 'circularity' from a largely techno-scientific perspective. Crucially however, *how do we ensure that when applying new technologies to develop future 'circular materials', we do not simply tread the same unsustainable path used to create our current linear material cultures?* To consider how to *terra-reform* our relationships with materials, we chose to combine the actionable insights of *physical prototyping* with the future-focussed envisioning of *Design Fiction prototyping* and explore the possible socio-technical benefits and burdens that potential future 'circular materials' may engender upon the planet.

Physical Prototyping

For our first stage of prototyping, we wanted to better understand the real-world feasibility of 'reprogramming' physical matter. To do this, we developed a physical prototype based on a design and fabrication approach which we term *Tuneable Environments* (Blaney et al, 2019) – a prototyping platform (Figure 2A) which allowed us to experiment with the notion of reprogramming matter by *modulating stimuli*. To construct our *Tuneable Environment*, we drew upon principles from two fields of architecture: (i) *Persistent Modelling* as established by Ayres (2012) which demonstrates how design information can be employed to shape physical matter (Ayers, 2011), and (ii) *Autonomous-Assembly*, where assembly information can be 'embedded' into physical materials by *pre-designing* their geometric properties and supplying them with energy (Tibbits, 2014; Tibbits et al, 2016).

Our current prototype iteration builds on work by Koelman et al (2015) and Seibold et al (2018). Figure 2B and 2C depicts how our prototype is capable of dynamically re-shaping ferrofluid into different two-dimensional patterns in real-time. This is made possible by modulating the magnitude, location and duration of the magnetic stimuli – a set of magnets that are attached to automated vertical actuator rods which we can programme and then control.

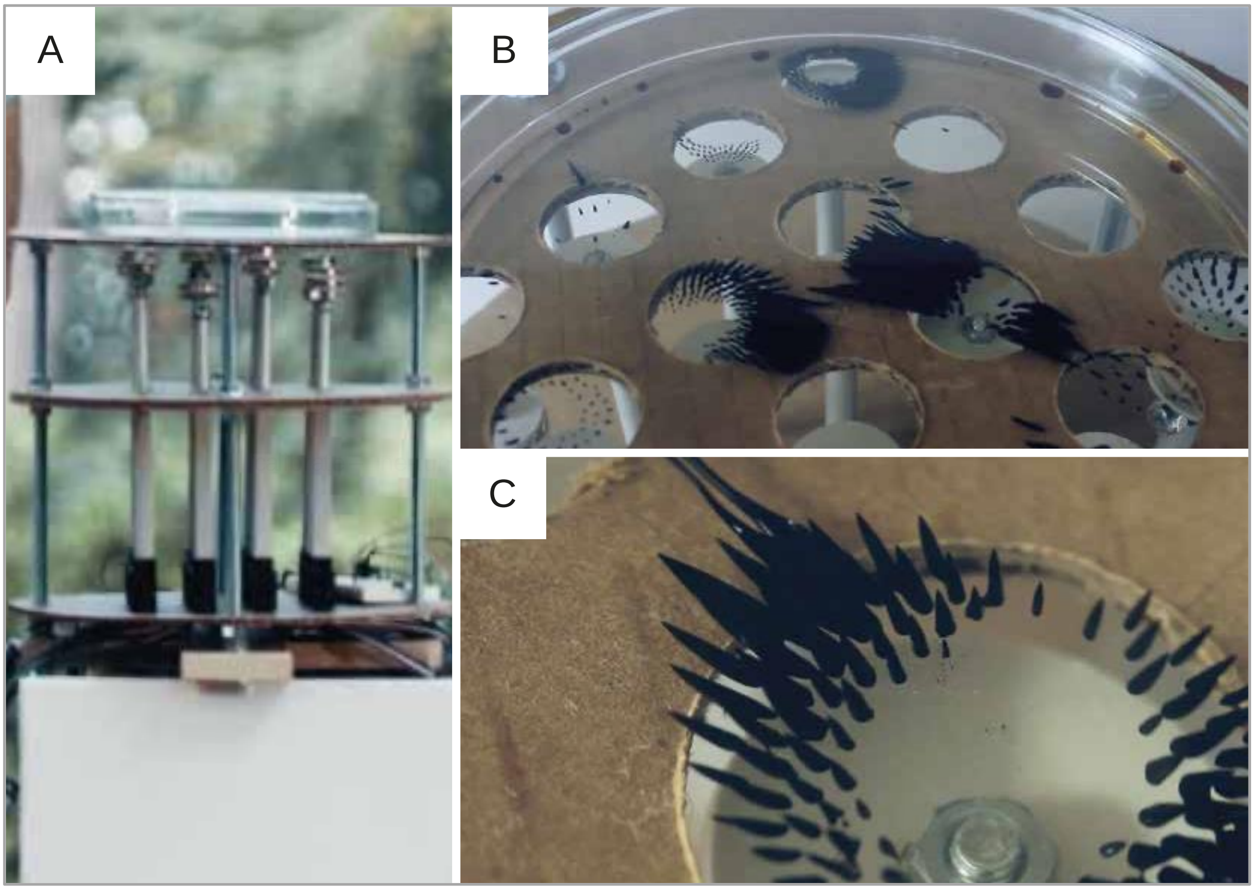

Figure 2. For our first stage of prototyping, we experimented with the potential for physical matter to be infinitely reprogrammed using a design and fabrication approach termed Tuneable Environments. Image credit: Authors (2021).

For our second set of experiments, we built upon work by Raj et al (2001) and Oh et al (2005). Figure 3 shows how we utilised the *Tuneable Environment* prototype to try and reprogram small-scale three-dimensional structures made from ferrofluid combined with wax. The first stimuli – heat – was used to melt the 'ferro-wax' (Figure 3A), and then the second stimuli – magnetism – enabled us to move the material around an earring shaped scaffold (Figure 3B). Figure 3C depicts the point at which we ‘uploaded’ digital design assembly information ‘into’ the ferro-wax to temporarily ‘freeze’ the matter into the three-dimensional earring structure. Importantly, we were then able to remove the ‘programmed’ earring from the prototype’s tank and physically interact with it. After returning the earring to the tank, we again subjected the material to the stimuli (heat and magnetism) which ‘reprogrammed’ it, that is, it was reconfigured into a new abstract three-dimensional structure.

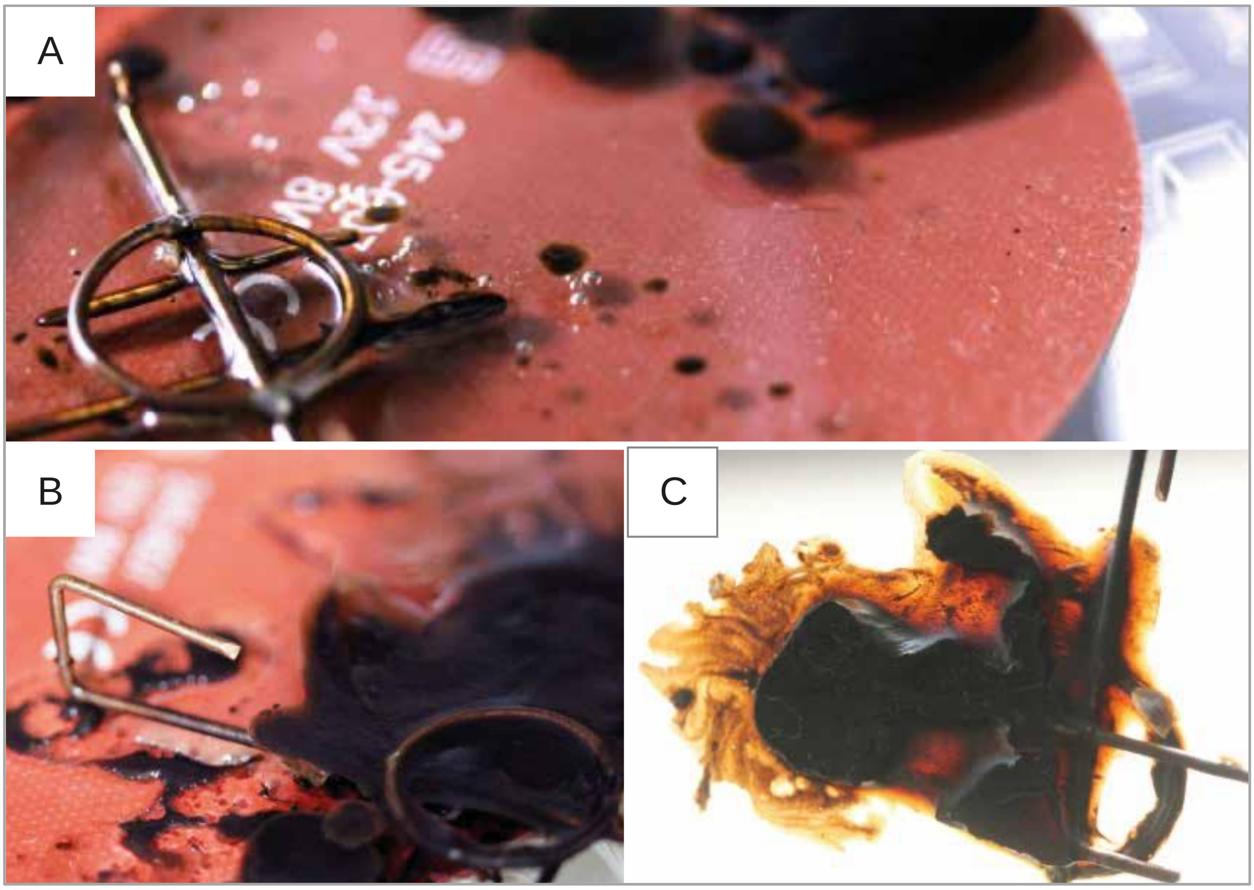

Figure 3. Our secondary experiments using ‘ferro-wax’ to fabricate a 3D earring product. Image credit: Authors (2021).

Although extremely low fidelity, we believe our initial explorations provide meaningful insights into the potential for reprogramming matter using a multi-stimuli system. This capability sits in contrast to current fabrication processes which impose permanent form upon synthetic materials rendering them difficult to reconfigure and reuse. As such, our physical prototyping is valuable in that it provides a ‘jumping off point’ for us to speculate regards the implications of adopting *Tuneable Environment* and *Reprogrammable Matter* related technologies across society in the future – particularly their relationship to planetary sustainability. In essence, could such technologies provide the basis for future *circular materials?*

Design Fiction Prototyping

For our second stage of prototyping, we utilised *Design Fiction as World Building* techniques to envision a near future where *Tuneable Environment* and *Reprogrammable Matter* principles have been widely adopted in society. Like the related fields of *Critical Design* (Dunne & Raby, 2013) and *Speculative Design* (Auger, 2013), the creation of fictional prototypes is central to *Design Fiction* practice. Yet, where *Critical* and *Speculative Designers* draw upon a predominantly artistic heritage (for example, their prototypes often exhibit an abstruse gallery-like aesthetic), both the roots and semantics of *Design Fiction* emanate from the more quotidian technological vernacular of popular science fiction literature and film (Stead, 2020). Moreover, unlike the other two practices, the concept of *world building* is core to *Design Fiction* proposals. As Coulton et al (2017) assert, when collections of *Design Fiction* prototypes are viewed together, they begin to build a proximate fictional world in which new technologies can plausibly exist and then be more thoroughly considered. Accordingly, we embodied our vision in the form of several *diegetic prototypes* – a fictional device called *Elixir* and the wider world in which the device inhabits. Given that *Design Fiction* prototypes are free of commercial constraints such as usability, aesthetics and cost, our fictive future for *Tuneable Environment* and *Reprogrammable Matter* is able to go beyond standard cycles of socio-technical innovation (Bleecker, 2009, Hales, 2013).

Figure 4A & B begin to concretise the world in which the *Elixir* device exists, in particular the way people would potentially interact with the technology and the associated *Reprogrammable Matter*. In this future, the fabrication of infinitely reprogrammable and scalable products is commonplace. Consequently, users can directly operate their *Elixir* to fabricate new objects from other mundane physical items as feedstock. In this way, our fictional world seeks to both reflect but also challenge the thinking that underpins the formation of a *Circular Economy* (Ellen MacArthur Foundation, 2021) and the notion of *Cradle-to-Cradle* design (Braungart & McDonough, 2008).

Importantly, as with the adoption of any new socio-technical system, there would also be downsides and trade-offs that accompany our proposed technologies. The amount of energy required to perpetually power a network of globally dispersed fabrication devices that can reprogramme matter would likely be enormous. In our fictional world, the carbon emissions of these new technologies are superseding that of other 'big emitters' like the aviation industry and Internet streaming (Figure 4C). Might the sustainable gains they provide through waste reduction be quickly undermined by their vast energy usage and carbon emissions impacts?

Furthermore, while the problem of material waste also appears to be manageable through the introduction of domestic *Tuneable Environments* like *Elixir*, such technologies might also lead to *hyper-materialistic* societies which consume at a rate far beyond our current levels. For example, whilst the unsustainability of *fast fashion* is a contentious issue today, if *circular gold* can be fabricated as quickly and affordably as any other matter (Figure 4D), what ethical quandaries are raised in regard to *reprogrammable consumption*? Would such a future world be considered the *greater good* when it comes to tackling waste and pollution? By beginning to ruminate on such issue**s**, we aim for our fictional prototypes aim to generate a *discursive space* where the possible planetary implications of adopting the proposed technologies can be more thoroughly deliberated (Stead, 2016; Tharp & Tharp, 2018).

3.2. Positing Five Themes for Expanding DfT

Through our initial case study, we have begun to highlight some of the possible implications (both positive and negative) that may possibly result from further development of *Tuneable Environments/Reprogrammable Matter*. Given the positional nature of this paper, we acknowledge that additional testing of our approach is needed to push these discussions forward and develop DfT into a more robust critical framework. That said, having reflected upon our research process thus far, we propose five key themes for DfT which we believe warrant further exploration by our research team and potentially other designer-researchers:

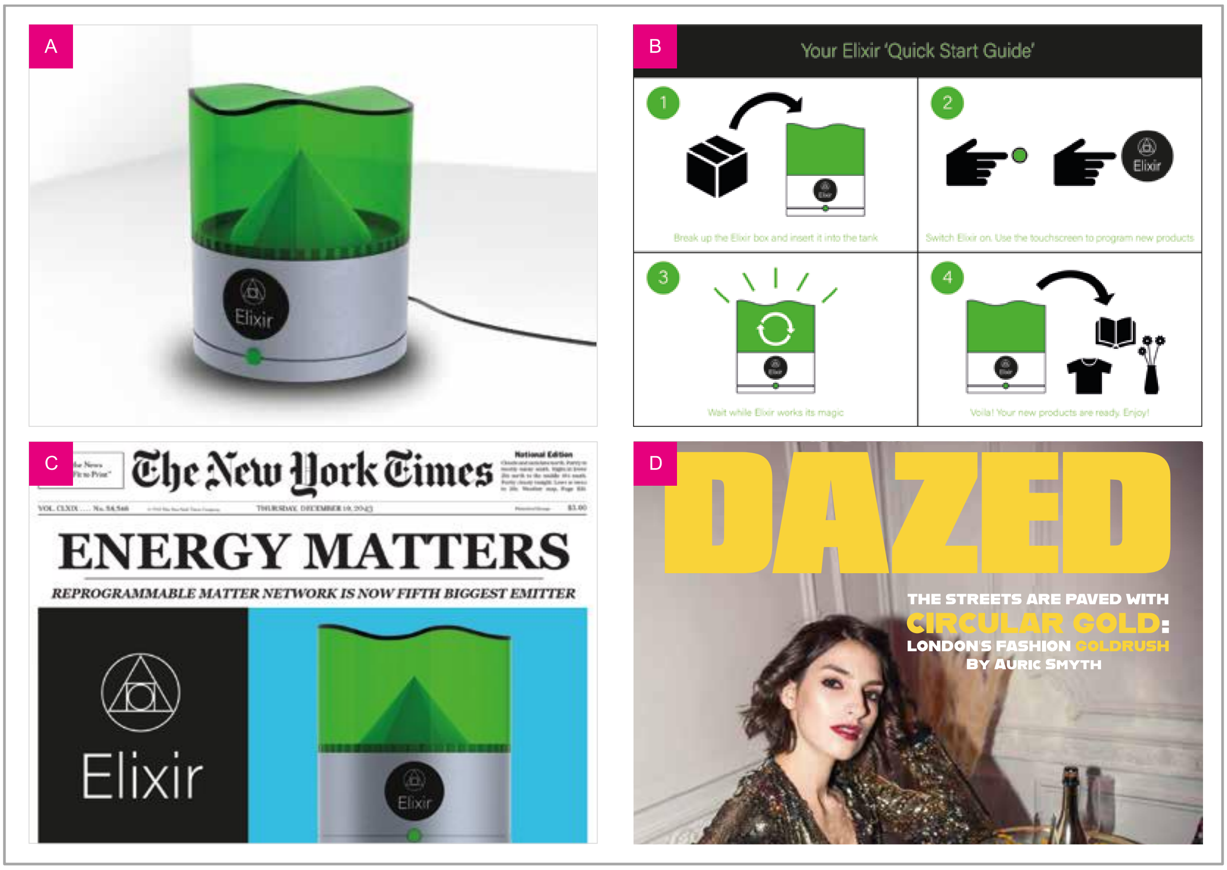

Figure 4. We utilised Design Fiction as World Building techniques to extrapolate the principles derived from our physical prototyping and begin to embody them in several fictional prototypes. Image credit: Authors (2021).

Synergy

By drawing upon the strengths of each technique, we contend that our case study has helped us to begin to cement the *liminal space* between *real-worldbuilding* (physical) and *fictional-worldbuilding* (Design Fiction) prototyping. Figure 5 shows that our DfT process was characterised by this synergetic relationship. As Rumpala (2021) contends, the combination of imagination and innovation present new opportunities for crossing the registers of science and creativity. Accordingly, we posit that there is also potential for our approach to be employed beyond the traditional disciplinary boundaries of 'design'. We see potential for DfT to be further evaluated by applying it in conjunction with other domains which employ prototyping techniques to explore socio-technical opportunities and challenges such as architecture, Human-Computer Interaction, engineering and manufacturing.

Generative Process

As well as drawing upon their strengths, we argue that our combined approach also begins to extend the possibilities of each prototyping technique. Work such as *Superflux's Mitigation of Shock* (2019) and Crawford and Joler's *Anatomy of AI* (2018) are recent examples of design-oriented research which aim to provoke discussion regards the impacts of technologies upon environmental sustainability. While both works are innovative and provocative, to a degree, each stands alone as a 'one off' statement. This can also be said of much *Design Fiction* practice (likewise both *Speculative Design* and *Critical Design*) which is often utilised to critique a particular socio-technical issue, device or system at a particular point in time. In contrast, real-world technological development tends to be iterative – it can shift and grow as time passes. Although this can often pose environmental risks for the real-world, fictional iterative prototyping would not. Thus, with Figure 6, we posit how the DfT approach would incorporate a *Design Fiction* prototyping process which could be both iterated upon and interrogated relative to its real-world counterpart. We believe such exploration might afford designers and technologists the ability to 'stay ahead' of their adjacent physical prototyping stream and cultivate a form of 'sustainable foresight', that is, fictional iterations could help said stakeholders to critically evaluate the possible environmental impacts that their real-world prototypes may have *before* these new interventions are implemented into society. This envisioning process might then also allow designers and technologists to begin to strategise and shape more environmentally responsible pathways for the future adoption of their real technologies. In addition to these posited sustainable benefits, we argue that applying *Design Fiction* in this generative manner would be novel and will grant important opportunities for our research team and others to further advance the methodological parameters of *Design Fiction* in *Future Work.*

Figure 5 Our DfT case study was defined by a synergistic relationship between real-world physical prototyping and Design Fiction prototyping. Image credit: Authors (2021).

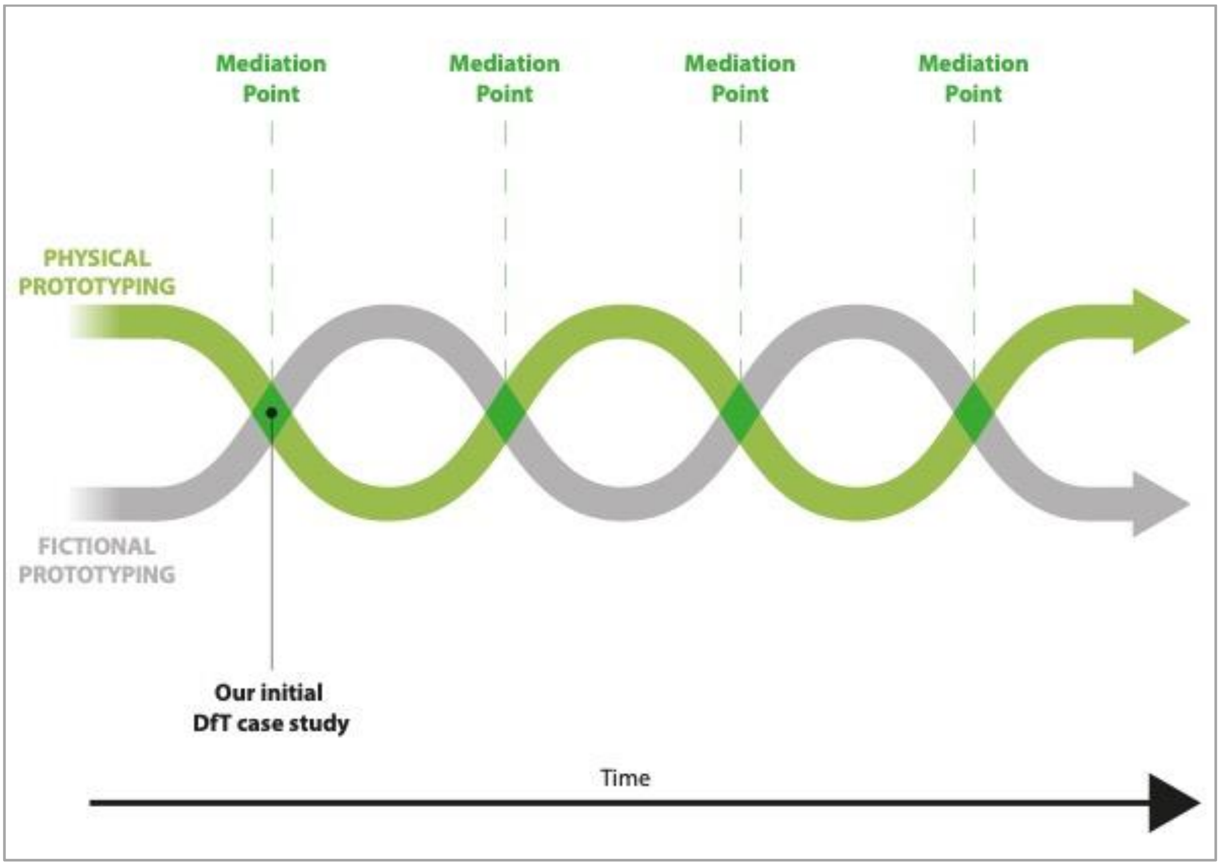

Figure 6. Generative and marked by Mediation Points, DfT would aim to help stakeholders gauge and mitigate the planetary implications of their developing technologies. Image credit: Authors (2021).

Mediation Points

As part of its generative competencies, we posit that our DfT approach could be marked by a series of what we have termed *Mediation Points*. As Bratton (2019) notes, due to humankind's deplorable track record, a sustainable future predicated on technological intervention is a *'venture that is full of risk* [and, as such,] *the future becomes something to be prevented as much as achieved.'* With a view to helping to reduce the environmental risk that future technologies may pose, we suggest that *Mediation Points* could be included at the intersections where the trajectories of real-world and fictional prototyping meet (Figure 6). In *Design Fiction* practice, prototypes are not seen as an attempt to predict the future or design a specific 'product solution' but as a strategy for opening *discursive space* where the potential value and meaning of the envisioned future world can be debated (Stead, 2016; Tharp & Tharp, 2018). With the above in mind, we posit that *Mediation Points* could be fertile ground for facilitating stakeholder discussions regards the possible planetary implications of advancing their technologies. Voicing possible concerns at these junctures may offer opportunities to stymy the 'tunnel vision' determinism and utopian rhetoric that can often characterise socio-technical progress (Friedman & Nathan, 2010; Nardi, 2016). To this end, *Mediation Points* might grant stakeholders the freedom to contemplate a plurality of environmentally responsible socio-technical futures and cultivate 'sustainable foresight' which can consider the broader sets of ecological values, alternate realities and emerging complexities that were not foreseen at the outset of the prototyping journey.

To illustrate our points, we have situated our *Tuneable Environments/ Reprogrammable Matter* case study on Figure 6. In essence, this paper forms part of our case study's first *Mediation Point* and seeks to open up discussion on the 'sustainable foresight' which may be required to mitigate the possible impacts that these formative technologies could impinge upon the planet in the future.

Scalability

From a city-serving carbon sequestration plant to a singular IoT health wearable device, our socio-technical interventions differ in size and shape – yet all have the potential to contribute to an unsustainable world. To this end, we wish to understand the potential for DfT to interrogate the sustainable implications of technological development across a variety of scales (Figure 7).

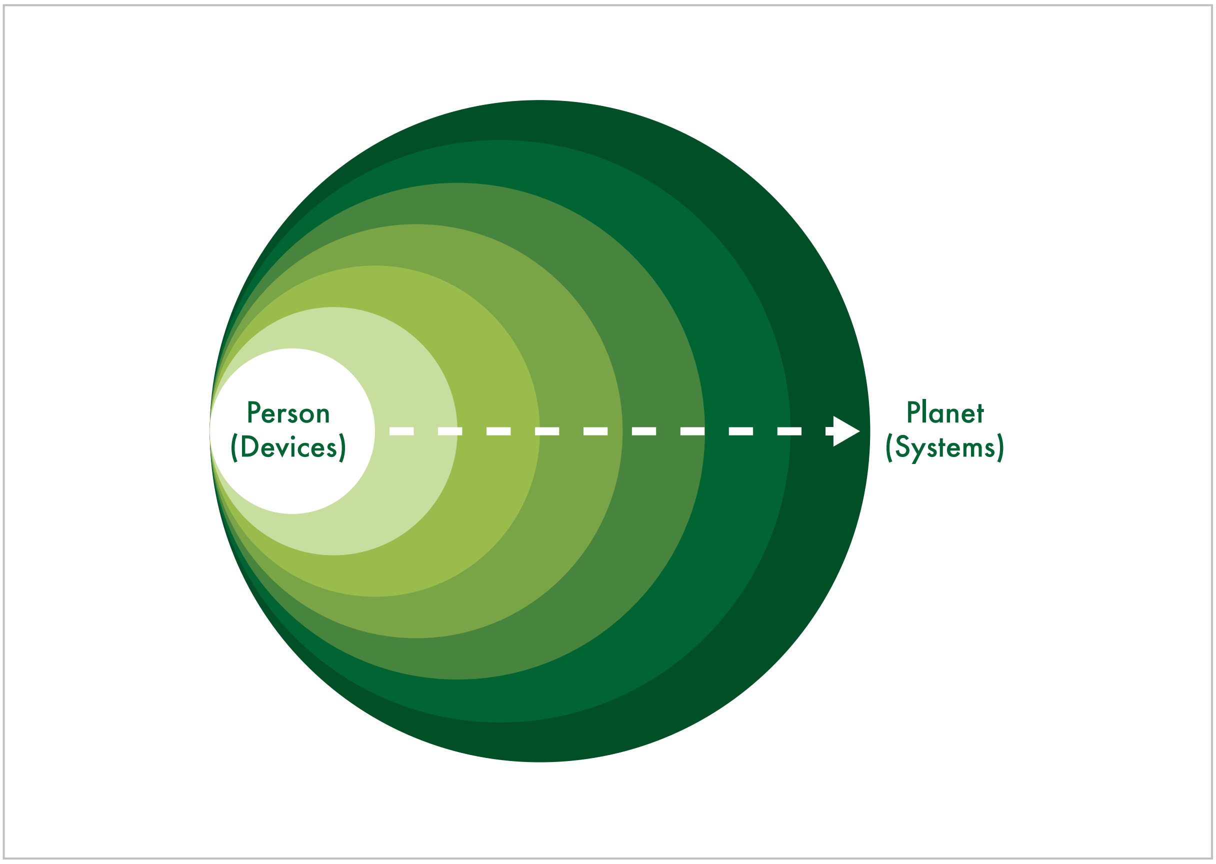

Figure 7. DfT could potentially be employed to interrogate socio-technical challenges of various scales. Image credit: Authors (2021).

Governance

Acknowledging the environmental and ethical dilemmas that new technological interventions can pose, Jean Buck (2019) argues against viewing such challenges through the simple binary of climate justice and degrowth versus the ardent solutionism as espoused by the *Ecomodernist* group (Asafu-Adjaye et al, 2015). Indeed, the extent of planetary repair now required warrants not just radical technologies but also profound ideological and economic transformation, a future where climate restoration is considered a social necessity. Thus, as Mann (2021) stresses, this evolution must not happen solely at the hands of technological stakeholders. It is crucial that the pathways for tackling climate change must also have strategic and systemic parameters. Though further work, we therefore want to ascertain whether *Mediation Points* could be potential platforms for actively combining sustainability, ethical, civic, political, financial *and* technological stakeholder voices and stewardship.

5. Conclusion

Given the urgency with which we must respond to the climate crisis and the widely perceived benefits of employing technologies to counter such problems, a new critical framework for governing the threats new technologies may pose to environmental sustainability is urgently required. By bridging real-world and fictional-world prototyping, we contend that our case study begins to help us to define some of the possible practical and theoretical foundations for such an approach. Through further case studies, we intend to continue to augment and test our DfT process – all with the aim of contributing to the responsible *reforming* of our planet.

References

Akrivos, V., Haines-Gadd, M., Mativenga, P., Charnley, F. (2019). Improved metrics for assessment of immortal materials and products. 26th CIRP Life Cycle Engineering (LCE) Conference. DOI:10.1016/j.procir.2018.12.012

Asafu-Adjaye, J., Blomqvist, L., Brand, S., Brook, B., Defries R., Ellis, E., Foreman, C., Keith, D., Lewis, M., Lynas, M., Nordhaus, T., Pielke JR, R., Pritzker, R., Roy, J., Sagoff, M., Shellenberger, M., Stone, R., & Teague, P. (2015). 'An Ecomodernist Manifesto.' Retrieved May 10, 2021, from: https://static1.squarespace.com/static/5515d9f9e4b04d5c3198b7bb/t/552d37bbe4b07a7dd69fcdbb/1429026747046/An+Ecomodernist+Manifesto.pdf

Auger, J. (2013). 'Speculative Design: Crafting The Speculation,' *Digital Creativity*, 24;1, 11–35. DOI:10.1080/14626268.2013.767276

Ayres, P. (2011). Free-from Metal Inflation & the Persistent Model. In FABRICATE 2011. Eds Glynn, R and Sheil, B. UCL Press.

Ayres, P. ed., (2012). Persistent Modelling: Extending the Role of Architectural Representation. London: Routledge.

Bleecker, J. (2009). Design Fiction: A Short Essay on Design, Science, Fact and Fiction. Retrieved May 10, 2021, from http://drbfw5wfjlx on.cloudfront.net/writing/DesignFiction_WebEdition.pdf

Bishop, G., Styles, D., & Lens, P.L.N. (2020). Recycling of European Plastic Is A Pathway For Plastic Debris In The Ocean. Environment International, Volume 142, 105893, https://doi.org/10.1016/j.envint.2020.105893.

Blaney, A., Alexander, J., Dunn, N., & Richards, D. (2019). Designing Parametric Matter. 367-396. Paper presented at International Association of Societies of Design Research Conference 2019 , Manchester, United Kingdom. https://espace.mmu.ac.uk/626769/1/Design%20Revolutions%20IASDR%202019%20Proceeding%20Vol2.pdf

Bratton. B.H. (2019). *The Terraforming*. Strelka Press.

Braungart, M., & McDonough, W. (2008). *Cradle to Cradle: Remaking The Way We Make Things*. London: Vintage.

Coulton, P., Lindley, J.G., Sturdee, M., & Stead, M. (2017). 'Design Fiction as World Building,' in Proceedings of Research through Design Conference (RTD) 2017, Edinburgh, UK. doi.org/10.6084/m9.figshare.4746964.v2

Crawford, K., & Joler, V. (2018). 'Anatomy of an AI System.' Retrieved May 10, 2021, from https://anatomyof.ai

Dictionary.Cambridge.org. (n.d.). Terraforming. Retrieved May 10, 2021, from https://dictionary.cambridge.org/dictionary/english/terraform

Dourish, P., and Bell, G. (2014). '"Resistance Is Futile": Reading Science Fiction alongside Ubiquitous Computing,' Personal and Ubiquitous Computing, 18(4). DOI: 10.1007/s00779-013-0678-7

Dunne, A. and Raby, F. (2013). *Speculative Everything*. London: MIT Press.

Ellen MacArthur Foundation. (2021). Universal Circular Economy Policy Goals: Enabling The Transition To Scale. Retrieved May 10, 2021, from https://www.ellenmacarthurfoundation.org/publications/universal-circular-economy-policy-goals-enabling-the-transition-to-scale

Findeli, A. (2004). La Recherche-Projet: Une Méthode Pour La Recherche En Design. Symposium De Recherche Sur Le Design Tenu à la HGK De Bâle Sous Les Auspices Du Swiss Design Network les 13-14 mai 2004 et publiée en allemand dans Michel, R. (dir.), Erstes Designforschungssymposium, Zurich, SwissDesignNetwork, 2005, pp.40-51.

Fogg, M.J. (1995). *Terraforming: Engineering Planetary Environments*. SAE Press, ISBN 1-56091-609-5.

Forti, V., Baldé, C. P., Kuehr, R., & Bel, G. (2020). The Global E-waste Monitor 2020: Quantities, Flows, and The Circular Economy Potential. Retrieved May 10, 2021, from http://ewastemonitor.info/wp-content/uploads/2020/12/GEM_2020_def_dec_2020-1.pdf

Frayling, C. (1993). 'Research In Art And Design.' Royal College of Art Research Papers, 1:1, 1–9.

Friedman, B. and Nathan, L. (2010). Multilifespan information system design: A research initiative for the HCI community. Proc. of CHI '10. 2243–2246.

Gates, B. (2021). *How to Avoid A Climate Disaster: The Solutions We Have and the Breakthroughs We Need.* London: Penguin Books.

Gaver, W. (2012). 'What Should We Expect From Research Through Design?' in Proceedings of the 2012 CHI Conference on Human Factors in Computing Systems. ACM, New York, (CHI 2012). May 5-10, 2012, Austin, Texas, USA. 937–946.

Global Climate Action (2020). Climate Ambition Alliance: Net Zero 2050. https://climateaction.unfccc.int/views/cooperative-initiative-details.html?id=94

Goidea, A., Dimitrios, F. & Andréen, D. 2020. Pulp Faction: 3d Printed Material Assemblies Through Microbial Biotransformation. *In:* BURRY, J. S., J. SHIEL, B AND SKAVARA, M (ed.) *FABRICATE.* London, United Kingdom: UCL Press.

Gradinar, A. I. (2018). Designing interactive objects and spaces for the digital public space. Lancaster University. https://doi.org/10.17635/lancaster/thesis/357

Hales, D. (2013). 'Design Fictions: An Introduction and Provisional Taxonomy,' Digital Creativity, 21:1, 1-9. DOI: 10.1080/14626268.2013.769453

Jean Buck, H. (2019). *After Geoengineering: Climate Tragedy, Repair, and Restoration*. London: Verso Books.

Koelman Z., Graaf, M. & Leeuw, H.. (2015). From Meaning to Liquid Matters. Proceedings of the 21st International Symposium on Electronic Art, pp.3553-3568.

Kolbert, E. (2021). *Under A White Sky: The Future of Nature*. London: Bodley Head.

Lovelock, J.E. (1979). *Gaia: A New Look at Life on Earth*. Oxford University Press.

Lovelock, J.E. & Allaby, M. (1984). *The Greening of Mars*. New York: Warner Books.

Mann, M. E. (2021). *The New Climate War*. PublicAffairs.

Milman, O., & Rushe, D. (2021). America's Race To Zero Emissions: The Latest Must-Have Among US Billionaires? A Plan To End The Climate Crisis. Retrieved May 10, 2021, from https://www.theguardian.com/us-news/2021/mar/25/elon-musk-climate-plan-reward-jeff-bezos-gates-investments

Mulvaney, D. (2014). Solar Energy Isn't Always as Green as You Think. Retrieved May 10, 2021, from https://spectrum.ieee.org/green-tech/solar/solar-energy-isnt-always-as-green-as-you-think

Nardi, B. (2016). Designing for the Future - But Which One?, Interactions, Jan-Feb, DOI: 10.1145/2843592

Oberg, J.E. (1981). *New Earths: Restructuring Earth and Other Planets*. Stackpole Books, Harrisburg, Pennsylvania.

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.

Pak, C. (2016). *Terraforming: Ecopolitical Transformations and Environmentalism in Science Fiction*. Liverpool: Liverpool University Press.

Piper, K. (2018). The Case Against Colonizing Space To Save Humanity. Retrieved May 10, 2021, from https://www.vox.com/future-perfect/2018/10/22/17991736/jeff-bezos-elon-musk-colonizing-mars-moon-space-blue-origin-spacex

Pandey, M. (2020). Jeff Bezos Earth Fund: How can $10bn fight climate change? Retrieved May 10, 2021, from https://www.bbc.co.uk/news/newsbeat-51544501

Ramirez, R. (2009). An Epistemology for Research through Design,' in Proceedings of the ICSID Design Education Conference, pp 1–14. Retrieved May 10, 2021: http://www.icsid.org/education/education/articles987.htm.

Raj, M. K., & Lennon, J. (2001). Ferrofluid Sculpting Apparatus. USA patent application.

Rumpala, Y. (2021). Science Fiction, Reconfigured Social Theory & the Anthropocene Age: Exploring & Thinking About Planetary Futures Through Fictional Imaginaries. Global Discourse, 11, 1-2, February, pp. 245-266(22). DOI: https://doi.org/10.1332/204378920X16050867405760

Sagan, C. (1961). The Planet Venus. *Science* 24 Mar 1961. Vol. 133, Issue 3456, pp. 849-858. DOI: 10.1126/science.133.3456.849 https://science.sciencemag.org/content/133/3456/849

Sagan, C. (1973). Planetary Engineering on Mars. *Icarus*. Volume 20, Issue 4, December 1973, Pages 513-514 https://www.sciencedirect.com/science/article/abs/pii/0019103573900262

Seibold, Z., Grinham, J., Geletina, O., Ahanotu, O., Sayegh, A., Weaver, J. & Bechthold, M. (2018). Fluid Equilibrium: Material Computation in Ferrofluidic Castings. ACADIA 2018: On Imprecision and Infidelity, 2018 Mexico City. pp.250-258.

Stahel, W.R. (2016). The Circular Economy. Retrieved May 10, 2021, from https://www.nature.com/news/the-circular-economy-1.19594

Stead, M. (2016). 'A Toaster for Life: Using Design Fiction To Facilitate Discussion On The Creation Of A Sustainable Internet Of Things', in Proceedings of DRS 2016, Design Research Society 50th Anniversary Conference. Brighton, UK. Available at: http://www.drs2016.org/455

Stead, M., Gradinar, A., Coulton, P., & Lindley, J. (2020). Edge of Tomorrow: Designing Sustainable Edge Computing. In Proceedings of the Design Research Society Conference 2020 (Situations ed., Vol. 1, pp. 88-110). [293] (Proceedings of the Design Research Society Conference 2020). Design Research Society. https://doi.org/10.21606/drs.2020.293

Stead, M. (2020). Spimes: A Multidimensional Lens for Designing Future Sustainable Internet Connected Devices. Lancaster University. https://doi.org/10.17635/lancaster/thesis/997

Strengers, Y. (2013). *Smart Energy Technologies In Everyday Life: Smart Utopia?* Basingstoke: Palgrave Macmillan.

Superflux. (2019). Mitigation of Shock. Retrieved May 10, 2021, from http://superflux.in/index.php/work/ mitigation-of-shock/#

Tharp, B.M., & Tharp, S. M. (2018). *Discursive Design: Critical, Speculative, and Alternative Things.* MIT Press, Cambridge, MA.

Tibbits, S., (2014). Fluid Crystallization: Hierarchical Self-Organization. FABRICATE. pp. 296-304 (9 pages) https://doi.org/10.2307/j.ctt1tp3c5w.40

Tibbits, S. (2016). *Self-Assembly Lab: Experiments in Programming Matter*. New York: Routledge.

Weetman, C. (2016). *The Circular Economy Handbook for Business and Supply Chains: Repair, Remake, Redesign, Rethink.* London: Kogan Page.

Williamson, J. (1942). Collison Orbit. Astounding Science Fiction, 29, 5, July.

UK Parliament. (2020). House of Commons Library: Plastic Waste. Retrieved May 10, 2021, from https://commonslibrary.parliament.uk/research-briefings/cbp-8515/

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