Sustainable approaches to textile design: lessons from biology

Professor Veronika Kapsali[a], Dr Cathryn Aneka Hall

[a]University of the Arts London
*veronika.kapsali@fashion.arts.ac.uk
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Abstract: Models such as the circular economy, offer guidance to actors from the fashion and textile industry on how to navigate the negative environmental, ethical, and social impacts of the sector's current and historic practices. The principles underpinning these models originate from the intersection of biology and general systems theory and have provided us with valuable alternative paradigms via a top-down lens. This paper seeks to explore the potential for additional insight into sustainable textile design practice from biology by reviewing sustainable design principles emerging from top-down (ecology + systems view) within the context of a bottom-up (biology + engineering) approach for opportunities to mitigate the environmental impact of design decisions informing the physical products we consume. The results suggest a novel practice-based conceptual framework that could enable textile designers to better understand the impacts of resource efficiency, *longevity* and *recovery* of their design practice by shifting from a *substance* and *energy* approach to designing with *structure* and *information*.

Keywords: sustainable; biomimetic; circular design; textiles

1. Introduction

The fashion industry is responsible for 10% of global carbon emissions, according to research published by the European Commission (2019). This marks one of many roadmaps seeking activities that could enable us to navigate our way out of this age of waste and into a sustainable, possibly regenerative space. Models such as Cradle to Cradle (Braungart & McDonough, 2002) and the Circular Economy (Ellen MacArthur Foundation, 2013) propose a shift from linear to circular resource flow. These in turn have inspired approaches for new practice within the fashion and textile industry (F&TI) such as the introduction of innovative business models that go beyond reselling (second hand/ vintage) and repair (mending of garments) to borrowing models from other industries such as rent/leasing of apparel. Although we are the first generation to know that we are destroying our planet (World Wildlife Fund, 2019) and consumer awareness of F&TI environmental impacts has improved, this has yet to reflect on our collective behaviour as consumers (Zhang, Zhang, Zhou, 2021; Wagner, Heinzel, 2020). But what about the role of the designer?

Papanek (1972) discerns that few professions are more harmful to the environment than designers. Every design decision made in the planning of a product or service has some form of social, economic and environmental impact. As the design profession has become more aware of this, we have developed a series of strategies to mitigate the negative impacts of the decisions we make. In the textile sector, these include reclaiming pre- and post-consumer waste streams in a Design for Cyclability approach (Goldsworthy, 2014), Zero Waste Design (Rissanen & McQuillan,2016; McQuiilan 2020), adapting principles from Design for Disassembly (Forst, 2020) and using waste streams from other industries such as agriculture and the food industry (Stenton, Kapsali, Blackburn & Houghton, 2021).

This paper reviews sustainable design principles emerging from top-down (ecology + systems view) and bottom-up (biology + engineering view), to enhance our understanding of what nature can teach us in order to create reduced impacts through design in the F&TI using a bottom-up approach.

2. Background

2.1 Top-Down

Sustainability is defined as the *ability* to *sustain* certain rates or levels (Oxford Languages, n.d.). Events leading to the first fuel crisis in 1973 highlighted the scale of our dependence on fossil fuels and their contrasting finite nature. In the late 1969, an interdisciplinary group of scientist founded the New Alchemy Institute to seek alternative paradigms, and demonstrate the possibility to live within a society whose infrastructure did not rely of fossil fuels and other polluting industrial practices such as the use of pesticides in modern agriculture. The research outputs built on the transdisciplinary framework from general systems thinking (Von Bertalanffy, 1950) to include concepts from ecology (branch of biology that studies the relationship between organisms and to their physical surroundings). The resulting ecosystem model informed a pioneering set of strategies (such as renewable energy and organic farming) that enabled a small community to survive with minimum reliance on fossil fuels (Wade, 1975).

At a similar time, iconic industrial designer Victor Papanek considered how design can contribute to this discourse. In his seminal book: Design for the Real World: Human Ecology and Social Change, Papanek (1972, p186-214) maps out opportunities for biology to inform ecological strategies for industrial design. Although, we are not presenting an exhaustive review of the discourse within the subject of environmental sustainably in the 60’s and 70’s, it is clear that pioneering ideas emerged both via the sciences and humanities during this period.

2.2 Bottom-up

However, there is another perspective that is less studied by the creative design sector. Brothers Otto and Francis Schmitt, began to explain biological phenomena using the models and methods of physics and chemistry since the 1920’s in the US. Otto, the youngest sibling, focused his post-graduate studies on modelling the communication mechanism between squid nerve ends using principles from electrical engineering. This interdisciplinary approach is known today as biophysics. Otto was interested in applying this new knowledge from biophysics into new technology. He did not devise a name for *applied biophysics* until the 1960’s when he coined the term *biomimetic* to explain his approach to innovation. *Bionic* was another term created by Otto’s peers at the US air-force who had gained interest in this space (Schmitt, 1963).

Although, this work was not directly concerned with the environmental impacts of the industrial world, it did take a human-centred approach in the sense that it was motivated by seeking lessons from biology that can help us design/invent things that are useful for humans (Harkenss, 2004). Among Otto’s inventions are the Schmitt trigger (an electronic switch used in key boards to convert pressure into a signal) and later the field of biomedical engineering (the application of engineering principles and design concepts to medicine and biology for healthcare purposes).

Today, the grand narratives underpinning our perspectives on sustainable or regenerative models are defined by a top-down approach which serves a very important purpose in terms of signposting problems and potential solutions. However, a shift in perspective to a bottom-up approach could offer insight in terms of specific and practical design lessons.

3. Methodology

A *design principle* is a value statement that determines the most important goals a product or service should deliver for users; its purpose is to frame design decisions. From a top down perspective we consider: the circular design guide (Ellen MacArthur Foundation & IDEO, 2018), Teds Ten (Centre for Circular Design, 2021), Biomimicry 3.8 (Biomimicry 3.8, n.d.) and Nature Inspired Design (Tempelman et al., 2015), as authoritative sources of sustainable design principles which are drawn on extensively by the design community. We also utilize the comprehensive study of design for sustainablility (DfS) conducted by De los Rios & Charnley (2017), as a baseline to ensure we capture the most widely used guides and terminology.

We checked for potential gaps in the range of DfS approaches via a literature search using the keywords ‘sustainable design’, ‘circular design’, ‘sustainable design principles’, ‘circular design principles’, ‘sustainable design guide’, ‘circular design guide’, ‘sustainable textile design’ ‘circular textile design’. For each manuscript, preliminary relevance was determined by title and abstract. We searched Google Scholar, Web of Science, and EBSCOhost. The name and definition of design principles were recorded from the relevant manuscripts.

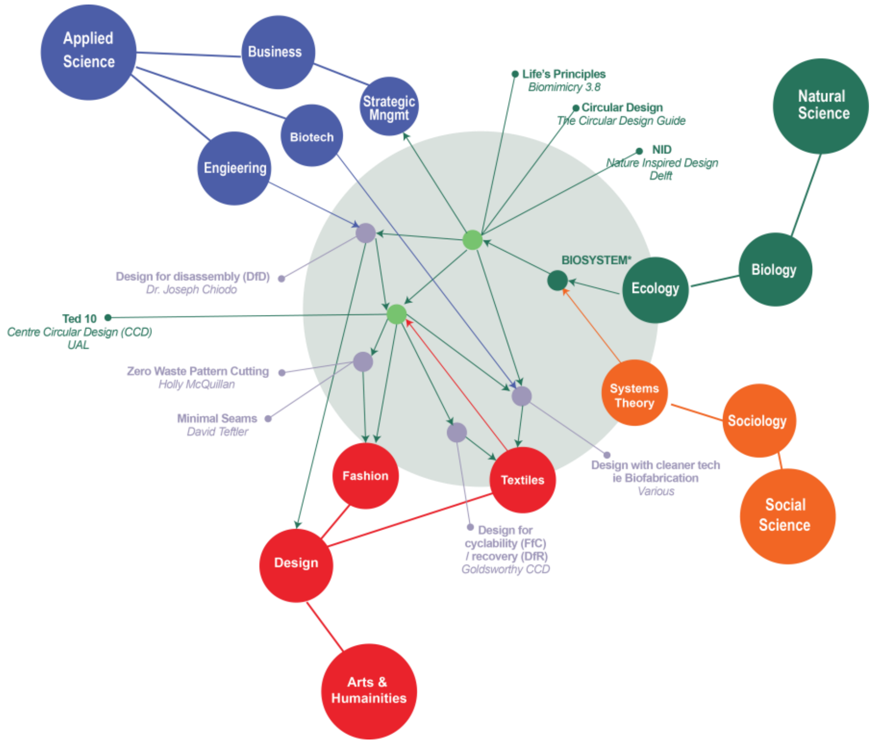

Figure 1: Interdisciplinary map of established sustainable design approaches (dark green lettering) and design practice (lilac lettering) in relation to the knowledge bases that inform them.

Design principles from the bottom-up approach were drawn from the formative research conducted on this topic by Vincent et al (2006) whose work assumes that the driver for change in both biology (adaptation, evolution) and human engineering is based on the resolution of technical conflicts. The research team, composed of engineers and biologist, set out to study the difference between solutions to design problems in the technical and biological spheres.

The team constructed a framework to enable the analysis of design problems across both spheres. The framework is based on THINGS, DO THINGS, SOMEWHERE. Specifically, THINGS refers to the substance (matter) and structure (the way matter is combined and organised across scales); DO THINGS denotes energy (the power that drives the action) and information (the instructions that define and trigger the action); SOMEWHERE relates to space and time, this aspect is outside the scope of our current study. Although the approach can be regarded as reductionist, the research methods remain the most rigorous, variation-based, comparative analysis between biology and technology on the topic of design solutions from an engineering perspective.

We distilled design principles from Vincent's analysis of the biology/ engineering review (ibid), while remain mindful of the philosophical differences between textile and engineering design. The resulting range of design principles from each source is reviewed and discussed within the context of textile design.

4. A Top-Down Approach

4.1 Interdisciplinary mapping of bio-related disciplines and design

The interdisciplinary interactions between biology and design that define the current range of sustainable textile practice, are not always transparent. The bio- prefix is used ubiquitously in terminology that functions more as a brand rather than an indicator of the specific disciplines or areas of knowledge that have informed the practice (Kapsali, 2022).

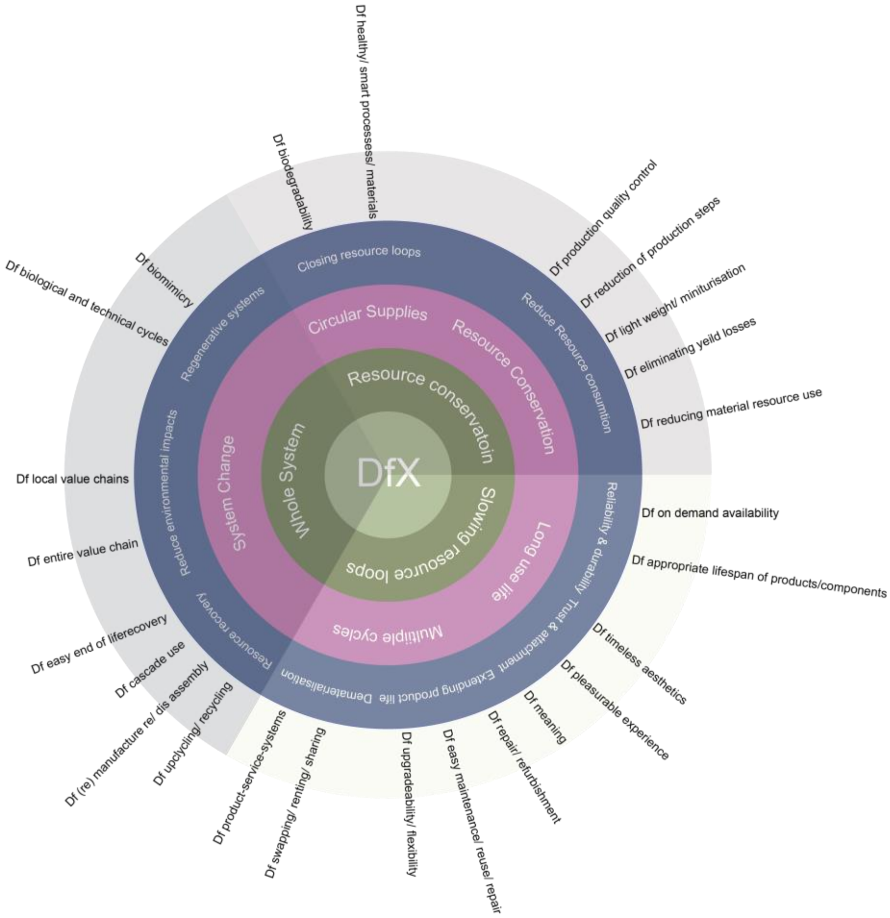

Figure 2: Work in progress thematic analysis of data on design for sustainability from literature review

To trace the link between these concepts, we mapped key DfS design approaches in terms of the disciplines that informed them, as illustrated in figure 1. This map highlights the relationship between key sustainable approaches to design that are relevant to the F&TI. For example, *design for disassembly (DfD)*; Johnson & Wang (1995) were among the pioneers of sustainability driven design for disassembly from a waste management perspective. In 2005, industrial designer and researcher Dr Chiodo produced a set of design guidelines specifically for consumer electronics (Chiodo, 2005), more recently textile designer and researcher Dr Forst published research focused on design for disassembly of garments (Forst, 2020). These examples embody approaches to understand and mitigate the problem of reclaiming resources from products at the end of their use lives via a *bio-systems* framework. Figure 1 highlights the indirect link of DfD to biology via ecology and systems theory.

4.2 Sustainable design principles – top-down

We compile the range of principles resulting from the top-down literature search into a list of design for sustainability (DfS). The DfS list consolidates the data from the analysis of resources from authoritative sustainable organisations with the data extracted from De los Rios & Charnley (2017), figure 2 illustrates a snapshot of visual exercise in organising data from the DfS list, thematically. The contents of the list are regarded as indicative rather than exhaustive. We observed a large range of terms used to describe the same or similar values, for example design for recycling or disassembly is expressed using different terms across several themes i.e. *design for ease of end of life recovery, design for remanufacture, design for reassembly*, we consolidated these according to their meaning within the context of design (see Table 1).

We consolidated the dataset (list of DfS priciples) and categorise according to pertinence to production process. The non-tangible category includes aesthetic and wider system view aspects. The resulting groupings are not difinative, principles can span across several categories. The purpose of table 1 is to present a view of the range of principles.

Table 1: Categorise of DfS principles

Non-tangible	Manufacture	Material	Use	End of life
timeless aesthetics	(re)manufacturing	biodegradability	easy maintenance	biological and technical cycles
biomimicry	eliminating loses	healthy materials/ processes	upgradability and flexibility	easy end-of-life recovery
pleasurable experiences	quality control		easy reuse and repair	swapping, renting and sharing
entire value chain	reducing resource use		cascade use	repair/refurbishment
meaningful design	reduction of production steps		appropriate lifespan	upcycling/recycling
local value chains	light weighting, miniaturizing			dis- / re-assembly
on demand or on availability				
product-service systems				

5. Bottom-Up Approach

5.1 Substance versus structure

If we consider an atom as the basic building block that forms the molecules of our materials and compare the range of elements that compose living organisms with the range employed within the technical sphere, we observe two distinct approaches. In biology, the range of basic building blocks is primarily limited to carbon, nitrogen, oxygen, hydrogen, calcium, phosphorous and sulphur as main ingredients. We know from chemistry, that molecules formed by these components tend to occur in ambient conditions and result in low molecular weights. This means that due to the relatively low energy that is involved in the creation of the molecules, their bonds are relatively easy to break and degrade easily.

In the technical sphere, we draw on the 118 elements of the periodic table to use as building blocks. We have developed technology that allows us to build molecules with higher molecular weights, these are stronger, but require quite a bit of energy to build and similarly large amounts of energy to degrade. So the meaning of *substance* in the context of design problem/solution means that if we want a strong material (for example), we build heavy molecules which require a lot of energy but are relatively indestructible such as polytetrafluoroethylene (PTFE) otherwise known as Teflon.

The property of a material in biology, is determined by the configuration of its building blocks, these can merge to form clusters of polymer that in turn form nano[1]- scale strings, clusters of strings can form fibres and concentrations of fibres can form larger structures such as tissue, this is a simplified account of a hierarchical approach to design from nano- to macro- scale. For example Keratin is a molecule made of oxygen, hydrogen, nitrogen and sulphur, the molecules can be arranged in two different configurations, helical or sheet. In helical configuration the resulting structure at macro scale is soft, flexible strands of hair; in sheet formation the macroscopic result is horn which is tough and hard.

So in biology the complex synergies between simple building blocks within hierarchical structures across scales result in extraordinary properties from basic materials. In contrast, we rely on the chemical bonds and complex molecules to engineer the properties of our materials and structures.

5.2 Energy versus information

In the technical sphere we have global complex supply chains, raw materials are sourced in one location, shipped to a string of locations for different levels of processing and assembly before they are distributed to various destinations for consumption. *Energy* captured from the burning of fossil fuels powers the production of our everyday goods. According to research published by the Global Fashion Agenda et al. (2017), the global textiles and clothing industry was responsible for the production of about 1.715 billion tons of CO2 emissions in 2015. Power in biology is harvested from ambient conditions such as the sun, moisture and pressure, in addition to the conversion of raw materials i.e. via photosynthesis or digestion. The emerging field at the intersection of biotechnology and textiles seeks to harness these low energy processes to produce alternative materials for the F&TI using living cells and micro-organisms (Lee, Congdon et al, 2020).

We have to power every aspect of the creation of our products, as such solving problems is intrinsically linked to the use of energy and lots of it. Energy in the form of fuel/ food is scarce and difficult to come by in nature, as such organisms have evolved ways in which to draw on abundant energy sources from the environment such as sunlight and moisture to induce certain behaviours. This is achieved via *information* that is physically embedded within their structure, for example within DNA. Genetic information is physically coded using

[1] There are 1 million nano meters in a millimeter

sequences of four bases of nucleic acid, these bases form specific pairs with one another that are stabilized via hydrogen bonds forming a double helix. The purpose of the helix structure is to twist round its central axis to enable the packing of lots of information (nucleic acid pairs) within a compact space.

Information can be embedded into a structure at larger scale, for example the composition of a pinecone bract. Pinecones are made of wood which is primarily composed of cellulose polymers. The job of a mature pinecone is to protect the seeds from spreading when the weather is damp because this causes germination of the seed to happen too close to the parent tree. This is not ideal, the chances of the seed accessing the right resources (light and nutrients) to survive are limited because the seedling would have to compete with the established parent for resources.

The solution to the problem in this case (resulting from millions of years of evolution) is to create a package for the seeds that limits their dissemination only in favourable dry conditions. The pinecone is able to sense the level of moisture in the environment and close up when it is damp to protect the seeds. The mechanism is very simple, it does not rely on living cells or a nervous system. The pinecone bract (which is the part of the cone on which the seed rests) is composed of two types of dead wood cell, one which swells when it absorbs moisture and another that doesn’t, the combined effect is that when wet the swelling part pushes against the non-swelling cells it causes the bract to bend upwards locking in the seed. When the external conditions are dry again, the moisture evaporates away from the bract causing the swelling cells to return to their original position and open up the cone. Information is embedded within the design of the bract structure from nano- to macro to reversibly change shape in the presence of moisture.

5.3 Bottom up summary

The results of the analysis suggest that in the technical sphere, we tend to solve our engineering ‘design problems’ via *substance* i.e., using chemistry to create specific properties and *energy* i.e., increasing the power input into a product. In contrast, using the same lens from biology, ‘design problems’ are addressed via *structure* i.e., the way basic building blocks are organised to form a material and *information* i.e., the physical nature of instruction/code. The implications for the design sector are the provision of an alternative paradigm to the prevailing *substance +energy* model that underpins both historical and contemporary design and engineering practice. We could learn how to design with *information* and *structure*.

6. Lessons from biology and engineering: a bottom-up approach

The lesson from biology, based on section 5, is that the environmental impact of the design decisions informing the physical products we consume could be enhanced or mitigated if we worked out how to shift from designing with *substance* and *energy* to designing with *structure* and *information*. However, if we attempt to correlate the list of design principles from table 1 into either of these themes (design with structure, substance, energy, or information), we encounter a disjuncture. The list of design principles from the bottom-up approach can only be classified as approaches to manage the use of *substance* and *energy*. Which inspires an alternative approach to reviewing the findings.

If we consider *resource* the *substance* and *energy* that is invested in the products we create and consume, then could the lessons from the bottom-up approach (i.e. design with *structure* and *information*) show us how to use our resources:

a. *efficiently* by using the least amount of substance and energy,

b. *longevity* by ensuring that the resources, while captured within a particular product, have multiple uses and/or last as long as they need to and,

c. *recovered* at the end of their use life.

In summary, biology can teach us how to ensure resource efficiency, longevity, and recovery RELR (figure 3) via design with structure and information.

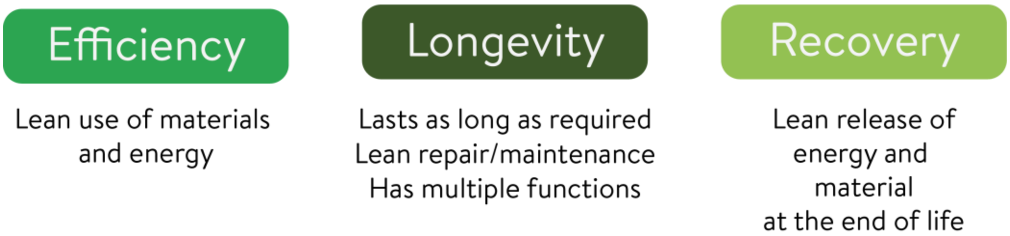

Figure 3: Design principles for resource efficiency longevity and recovery (RELR)

As textile designers, we are rarely involved in the chemistry of fibres and finishes, our main range of influence is via decisions on how to organise fibres into textile structures. There are several disciplines involved in this process, in general terms yarn spinning, textile structuring (knit, weave, non-woven), finishing (dying, calendaring etc.) and post-production manipulation (printing, embroidery, etc.). Within this context, *substance* refers to the fibres and materials (printing pastes, finishes, embellishments etc.) we draw on to create textiles, and structure denotes the various forms that can be created using the discipline specific techniques and tools. For example, a knitted textile designer can opt to create a plain knit structure or create a cable (technique), this can be done by hand or machine (tool). A mixed media designer might use pleating or smocking (technique) that can be created by hand or machine (tool).

Energy refers to the effort, fuel that is used to create a textile. This includes the energy involved in collecting the materials as well as manufacture. Regardless of whether this includes craft or industrial processes, production requires energy input (from burning fossil fuels) and effort (time/ calories) invested by the artisan or factory worker.

The role of *information* within this context, is less obvious because we are not used to embedding instruction into our textiles and when we do, the knowledge base for this resides within the tacit space (Polanyi, 2009) and is the subject of niche practice. One example is embodied within the work produced by Ann Richards, a weave designer who uses contrasting twist and fibres with different shrinking properties to engineer 3D structures from 2D woven textiles via washing or steaming (Richards, 2012). The example in figure 4 demonstrates how information (direction of yarn twist, pattern of weave) and structure (positioning of specific twisted yarn in warp or weft) combine to impact the efficiency of energy use for the manufacture of the final textile artefact.

Figure 4: Detail of woven textile structure in loomstate (left) and after wet finishing (right). The difference in texture between the top and bottom parts of the sample are implemented by the interactions between the different twists directions of the warp and weft yarns. Source: Richards, 2012

Pre-determined structural shape change (understanding of which is developed via investment of time and effort from the artisan) is implemented without additional effort from the maker, other than exposing the textile to water. This removes the need for additional processing steps such as pleating and heat pressing which require additional energy to implement. Unknown, non-tangible factors such as the artisan's unique metabolic rate, prevent a quantitative comparison between energy expenditure by the artisan to understand how to implement information into her textile structure, and the energy required to arrive at the same result via the substance and energy route. However, any energy spent for the development of skills and knowledge pertaining to the implementation of information into a textile structure by the artisan is transferable and not lost, as this can be reused in repeated actions or new contexts; an investment. Inversely, any energy spent on the processing of a flat textile into a textured one is lost once the transformation is complete; spent. The incineration of the same weight of treated and untreated textile would release the same value of kilo Watt hours (kWh)[2].

Another more recent development is the influence of *programmable design*[3] on textile practice, evident in the doctoral work of Jane Scott (Scott, 2018). Scott combines high twist yarns with knitted structures to create fabrics that reversibly alter their texture in relation to the levels of moisture in the environment (fig 5). Similar to Richard, Scott's work demonstrates how energy efficiency can be achieved via design with information. In this case reversible shape change behaviour is directly related to the level of moisture in the environment and requires no additional input from an external source. Consider a curtain that can alter its length in response to environmental conditions, this would require a complex system of sensors, actuators motors and processing devices within a material+energy context. However, the structure + information approach requires none of these.

Figure 5: Detail of knitted structure composed of yarns with differnet twist directions. The textile develops a pre-designed texture when exposed to moisture, the peaks (texture) dissapear when the sample dries. Source: Scott, 2018

The potential for longevity is demonstrated via the implementation of additional functions into the textile; the autonomous shape change property could be applied to a product that can adapt its behaviour such as its texture, thermal resistance, opacity etc thus combine the function of several products or devices.

Both Scott and Richard's work demonstrate enhanced resource recovery because of the mono-material nature of their textile outcomes. In the case of Richard's work, a sewing phase would introduce a binding element (sewing thread) that is usually a cotton polyester blend. Scott's work would typically incorporate electronic textile components such as a

[2] The kilowatt-hour (kWh) is a unit of energy equal to one kilowatt of power sustained for one hour.
[3] *Programmable* also *active* are new terminologies used within the context of design to describe structures able to self-assemble either via the use of motors (programmable origami paper) or material choice. This terminology has been used by Skylar Tibbits and collaborators to describe properties of some of the practical outcomes from the Self-Assembly lab at MIT.

power source, sensors and actuators. Due to their design, both examples can be easily integrated within a circular system because they retain a mono-material composition.

The creation of composite structures using polymers with different thermal shrinking properties also falls within the scope of efficiency and longevity but not recovery. Researcher, Walters (2018) takes a practice-led approach to develop lateral, heat induced shape change into textiles via the combination of thermal shrinking and non-shrinking yarns using a jacquard weave structure. Similar to Richard and Scott's work energy is salvaged from the reduction of processing steps (see figure 6).

Figure 6: Detail of Walters (2018) jacquard textile composed of yarns with different thermal shrinking properties. The textile is woven flat, then exposed to heat which causes one type of yarn to shrink more than the other creating forces within the textile that result in a 3D texture.

Examples of design with information and structure from a broader range of design disciplines can be found in artefacts created either by or in collaboration with the Self Assembly Lab at Massachusetts Institute of Technology (MIT), USA. Projects such as the Active Shoe[4] prototype created in collaboration with Swiss product designer Christophe Guberan. The technique combines additive printing with a stiff polymer onto a pre-stretched textile. The flat, 2D structure 'springs' into a 3D shoe form when the tension is removed from the textile. Information in this case is embedded in the structure via material choice (ie textile and stiff 3D print medium) and process (introducing pre-stretch into the textile and specific design of the printed component in 2D). Similarly, the Active Wood[5] projects combines knowledge of the way the components interact with moisture to inform the

[4] https://selfassemblylab.mit.edu/active-shoes
[5] http://www.christopheguberan.ch/active-wood/

design of the prototype composite material and control the way it bends and curls in the presence of moisture.

Longevity via emotional design (Van Hinte, 1997), recovery via design for recycling or disassembly (Kriwet, 1995) and cyclability (Goldsworthy, 2016) are examples of the mobilisation of resource efficiency, longevity and recovery within contemporary design practice. As discussed in section 4, these notions are informed primarily via a top down approach and provide strong, standalone theoretical frameworks that guide designers to think about the materials they use, the quality of design output i.e. how a product is valued by the consumer, and how it can be disassembled at the end of its life. The focus is on mitigating the impacts of design with substance and energy. The bottom up approach could offer a new paradigm that enables a shift from design with *substance* and *energy* to design with *structure* and *information*.

7. Conclusion

Goal n.12 of the UN's 2030 Agenda for Sustainable Development (United Nations, n.d.) emphasises the need to shift towards more sustainable consumption and production patterns. This research explores how design informed by biology can contribute to this goal by teaching us how to revere our resources and ensure the efficiency, longevity and recovery of the materials and energy invested in our products.

We discuss the use of resources (substance and energy) by combining lenses from engineering, biology, systems theory and textile design and identify two distinct approaches. A prevalent top-down view which has informed key thinking around alternative circular and sustainable models for design and manufacture from a systems perspective and a bottom-up approach emerging from the opportunities for applying research findings from biophysics into engineering and technological innovation.

We compare design principles resulting from the above study via the lens of resource efficiency, longevity and recovery (RELR). We find that principles emerging from the top down view focus on improving the use of *substance* and *energy*. However, the same approach from a bottom up perspective results in a completely new concept; RELR via design with *structure* and *information*. We present some examples of textile and broader design practice that exhibit elements of this approach (not necessarily informed by biology) and explore how RELR is implemented within the artefacts and prototypes.

We conclude that biology can teach us how to intentionally design with *structure* and *information*, in turn this could help us create products that genuinely consider the value of the resources invested, not from a fiscal but environmental perspective. Practical examples of this approach exist within a niche, research orientated space, however this paper suggests that there is unexplored potential within this new approach that is worthy of further study.

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About the Authors:

Professor Veronika Kapsali is Chair of Materials Technology and Design at The University of the Arts London. Veronika is also an AHRC Leadership Fellow on the topic of Bioinspired Textile Design.

Dr Cathryn Anneka Hall completed her PhD on Design for Textile Recycling in 2021 at the University of the Arts London (UAL). She is a post-doctoral research fellow on the Bio-inspired Textile project.