BROKEN BUTTERFLY WINGS: Exploring the role of textile blends in the circular economy for recycling and disassembly

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ABSTRACT
In the context of a transition to a more sustainable fashion and textile industry, blends (the bringing together of two or more different resources into one material) are a major issue. These are described as 'monstrous hybrids' and used to create 'Frankenstein products' that are difficult to recover and recycle. The circular economy champions mono-materiality where technical and biological materials are kept in separate cycles of the Ellen MacArthur Foundation's 'butterfly model' named because of its two wing-like sides. But in reality, materials are mixed in most of the textiles that surround us and fully mono-material design is unrealistic in many cases. The butterfly wings are broken. This paper explores the various ways textile designers make blends and acknowledges their role and creativity when providing solutions for aesthetic and technical requirements. The study draws on the first two authors' PhD practice research that explored this issue from complementary re-active and pro-active approaches. Both carried out at the University of the Arts London, one project investigated Textile Design for Disassembly and the other Design for Recycling Knitwear. Using an after-action review approach, joint insights from both projects are presented. The paper investigates blending across three themes: hierarchy, technique and fibre type. It focuses on why these themes are relevant to the designer and explores the complexity across them, before demonstrating how multiple perspectives are necessary to address the complex and systemic issues tied to blend recyclability. The paper concludes that blending and recovery are not mutually exclusive and that textile blends can, with forethought, form part of the circular economy.

KEYWORDS (5)
Textile design, Blends, Disassembly, Recycling, Circular economy,

1. INTRODUCTION

As the fashion and textiles industry is increasingly concerned for the environmental impacts it creates and attempts to transition to more circular and sustainable systems, the complexity of the issues to address become more pronounced. For textile designers, one of the major issues concerning recycling and circularity is the prevalence of blended textiles. Blending is defined by Sinclair (2014) as the bringing together of two or more different resources into one material. With the rise of cradle-to-cradle principles, referring specifically to the avoidance of combining technical and biological resources so they can be salvaged at the end-of-use, blended textiles have been labelled as 'monstrous hybrids' used to create 'Frankenstein products' (Braungart and McDonough, 2002). Notably, the Ellen Macarthur Foundation (EMF, 2013) circular economy model, commonly known as the 'butterfly' diagram with its two wing-like sides, follows the same cradle-to-cradle thinking of separate biological and technical flows. In the context of textiles this would mean natural and synthetic materials should never be combined and thus, has given rise to the two main Design for Recycling principles: mono-materiality and disassembly. In our current linear system, which wastes rather than circulates materials, the butterfly wings are broken.

This research opens up textile blending beyond the combining of biological and technical resources. It explores the vast array of ways that a textile designer can combine resources. The paper draws on two doctoral research projects by Author1 (Hall, 2021) and Author2 (Forst, 2020) which investigate this problem of blends for recycling in the circular economy and present two complementary approaches to addressing this, namely pro-active and re-active design (Goldsworthy, 2014). The first is conducted by Author2 pro-actively designing textile blends from the beginning of the process so that that can be disassembled at the end-of-use. The second is conducted by Author1 re-actively designing with the blends that already exists by controlling the blend ratios to extend the life of the resources.

The paper is split into two parts, first an after-action review method (Morrison and Meliza, 1999) was applied to both PhD studies which resulted in three ways of understanding blends: blending by hierarchy, blending by technique and blending by fibre type. In the second part Author1 and Author2's PhD research is presented as a case study demonstrating how these three categories of blending can be understood and applied by designers re-actively and pro-actively to provide design solutions to ease recyclability. The paper concludes that blending and recovery are not mutually exclusive and that textile blends can, with forethought, form part of an effective and viable circular economy.

2. METHODS

The methods used both in the two separate projects presented here, and in the comparative analysis of their response to the challenge of blends are inherently tied to practice research approaches. According to Kaszynska, Kimbell and Bailey (2022) definition's of practice research, its key components are that it should be embedded in real life situation and application, be grounded in relation to other bodies of knowledge and research, and transform both of these contexts. The work here is tightly connected to issues experienced in the textile and fashion industry, and it builds on research in the field of circular design (Ellen MacArthur Foundation and IDEO, 2017; Webster, 2017) and textile thinking (Igoe, 2021), aiming to offer new perspectives and practical tools for the site and the discipline. The definition of practice research also makes the place of reflective practice central, in line with the after-action review approach taken here.

Both researchers whose PhD work are used as case studies come from the field of textile design research and explore complementary perspectives on challenges of blends for designers. For Author1, whose practice is embedded within industry, this means relationship building and knowledge sharing with stakeholders throughout the textile production and recycling supply chain (Hall, 2018). Author2, whose practice stems from craft and is generally situated in the textile studio as well as local fab labs, developed solutions in exploratory making with felting, weaving, and laser cutting. This paper brings together and compares these two research projects to enable new insights on the challenge of blends in a circular economy context. The distance between the two practices also demonstrates the value of a thorough analysis of blends across the craft-to-industry spectrum.

This comparison of the two PhD projects uses an after-action review method (Morrison and Meliza, 1999) in which questions such as 'what happened?', 'what went well?', or 'what could be changed?' are asked. This simple approach helps consider the key components of the projects and understand what was gained from it. This approach led to the three types of blending by hierarchy, technique and fibre type being established. Although based on the understanding of blending developed in each PhD project, it was only through this after-action review method and comparison between the research that the were further contextualised.

In both individual projects, the active textile design practice element (developing recycled yarns and disassembly techniques) was followed by a review which adapts Schön's (1983) description of the 'reflective practitioner' to one that uses practice as a means for reflection. In both projects an extensive use of mapping and information visualisation was made to make sense of the complex data drawn into the research. This visualisation exercise is evidenced in the blend categories presented in this paper. As put forward by Arnheim (1969), visualisation of emerging ideas can support their development through 'visual thinking'. Tufte (2006) also supports the use of mapping and information visualisation to draw the viewer's attention to the key messages that discern in a set of data. For example, the enlarged models of textile blends shown in this paper were reviewed and rearranged through iterative mapping to produce the three classifications of blends presented. This use of a material object (which included both physical samples and images of a material object as seen in figures 3 and 4) rather than a graphical point (drawn representation of the material object) is described as media-visualisation by Manovich (2011) and supports a better understanding of the elements of the mapping as well as of their interdependencies. It was in combination with these sample-based mapping exercises that graphical methods were applied to sense make and therefore communicate clearly the different blending types.

3. THE PROBLEM OF BLENDING

WHAT ARE BLENDS?

Blending has been defined by Sinclair (2014:162) as "the bringing together of fibres of different types". She also distinguishes between mixing of the same fibre types, but here blending will be used as an all-encompassing term. The practice of blending different materials, revealed by Hatch (1993), can be traced back as early as 150 B.C. when cotton and flax yarns would be woven together to form a blended material. Blending within fabrics was used as a method from the 16th until 19th Centuries often to reduce costs. Blended with a yarn were not introduced until 1963. Since then, designers and manufacturers have found numerous creative ways to combine materials across the textile hierarchy.

Blends are also described as the combination of two or more different fibres in the same yarn or cloth (Hardingham, 1978). There are many reasons for combining fibres, but these are generally connected to the need to improve the performance of the materials (Sinclair, 2014). The combination of fibres with complementary characteristics is either aimed at improving the quality of the final product, or improving the efficiency of processing. Beton *et al.* (2014) also point out that, in some cases, blending can aid longevity and reduce environmental impacts, such as, incorporating a more durable component might extend the useful life of a fragile fibre. Another driver for the creation of blends is to reduce costs by, for example, combining a high-value fibre with a low-value one to balance the price (Hatch, 1993; Sinclair, 2014). The different reasons for combining materials lead to different types of blends, whether this is in fast-drying but comfortable poly/cotton sheets, or a cost-reducing wool/acrylic jumper. Above and beyond simple blending within a yarn or material, the many different methods used to construct textiles as well as a vast array of fibre types means that blending can become immensely complex.

We can see that the driver for blending textiles has come from innovation in the field of textiles engineering. However, there are other reasons that fibres are combined, such as aesthetics. Hardingham (1978), for example, considers blends which bring together different colours of yarn of the same fibre type such as in checked patterns in tartan fabric. Dormer (1997) describes creative textile practices using tacit skills to combine materials with contrasting textures and shines within the same cloth to create surprising and pleasing effects. Other blending techniques use different yarns or the application of a coating on the surface of fabric to achieve a specific pattern or finish. Such an ability to create combinations is an essential part of the textile designer's role, which is described by Igoe (2010:5) as being an "agent of tactile and visual experience, specifically decorative qualities".

WHAT IS THE PROBLEM?

Responsible design models such as cradle-to-cradle (Braungart and McDonough, 2002) and the circular economy (EMF, 2017) are increasingly being championed as industry best-practice. In essence, these models call for restorative design, where waste is a resource for the design of new products. This means that resources and products need to be re-used, repaired, re-manufactured and/or recycled to perpetually flow around the circular systems. One of the defining features of the circular economy model is it's two wing-like sides which is why it often referred to as the 'butterfly' model. Following cradle-to-cradle thinking, it separates biological and technical resource flows in each wing or cycle. This enables biological materials, such as organic cotton, to circulate by biodegrading as nutrients for new biological materials to grow, whilst the technical materials, such as polyester, can ultimately circulate through recycling. Therefore, blending these resources should be avoided and yet, the textile industry continues to use blending as a design and manufacturing tool. The butterfly wings are broken.

4. BLENDING: A DESIGN CHALLENGE

It is not, however just the biological and technical resources combined that create the problem for the circular economy. Many different types of textile blends do not fit into the circular model because they are difficult to recycle and end up as waste. In a circular economy model, waste is nothing but resources in the wrong place and blends are viewed as symptomatic of a design approach that prevents recovery. The inadvertent design of waste must be addressed, and this research suggests that it can be tackled through design itself.

However, as reported by EMF (2017) less than 1% of our textiles are recycled clothing-to-clothing. The barriers for this are connected to challenges in sorting the materials effectively (Dutch Clothing Mountain, 2017; Fibersort, 2018) the current lag in recycling technologies, both chemical and mechanical (Hall, 2018; Mathews, 2015), or the lack of markets for the resale of these resources (RSA, 2016; van Duijn, 2019) All of these point to the fact that textiles are still designed for a linear economy, and systems are failing to adapt to this. As put by Sophie Thomas:

> "We urgently need designers to visit end-of-life facilities so they can see for themselves how we are blindly designing waste into the system by creating products that are increasingly complex and harder to deconstruct and recycle" (RSA, 2016:3)

This call for a direct understanding of the systems within which material and products move is central to this research. If resources cannot circulate within the system, they cannot fit into the circular model. The design challenge, therefore, is to find effective alternatives to these material combinations which create barriers to recyclability by first, understanding the different methods of blending and then exploring re-active and pro-active design solutions to ease recyclability.

RE-ACTIVE AND PRO-ACTIVE APPROACHES

The concept of re-active and pro-active design approaches was presented by Goldsworthy (2014) in her paper 'Design for Cyclability: pro-active approaches for maximising material recovery'. A re-active approach to designing, Goldsworthy (2014) explains, begins at the point of disposal (Figure 1). It is at this point where the materials are assessed, and design can intervene in an attempt to return them back to use. However, as the materials are used, Goldsworthy explains, their value fades. This is always the case unless the material can go through a process of 'recovery' which should be repeated endlessly. This can be difficult to achieve through both mechanical and chemical recycling processes. Design, here, is reacting to a problem that already exists.

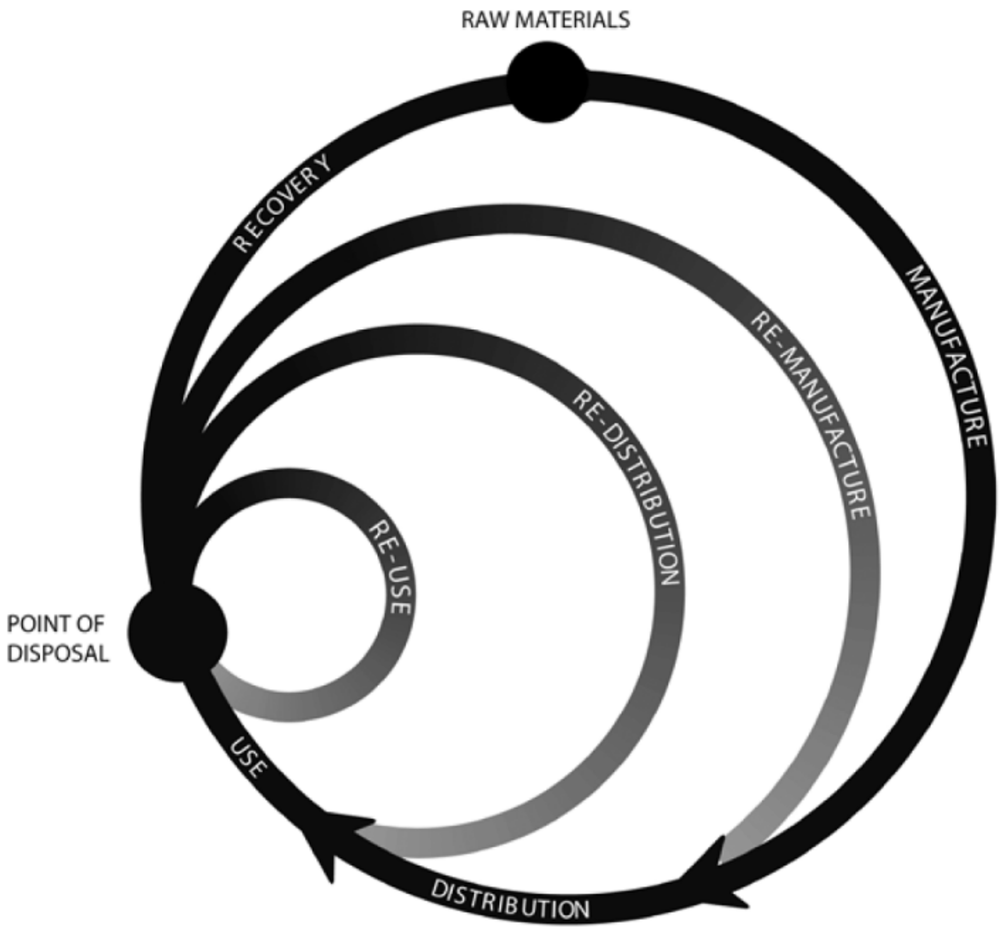

Figure 1. Four design approaches with the point of disposal as a starting point, (Goldsworthy, 2014)

In contrast, Goldsworthy argues that design should be taking the opposite approach and intervening much earlier in the cycle, at the raw material stage. She asks, “what if we identify the best possible routes for material value retention (recovery) and begin our design process from that point forward?” (Goldsworthy, 2014:8). This is a pro-active design approach, which starts from the beginning and “embeds future recycling into the very DNA of the products we design” (ibid). Goldsworthy concludes that for this approach to work recovery needs to be incorporated into the design brief. The key message that Goldsworthy provides is that design can be harnessed earlier in a product’s lifecycle in order to retain value at the raw material stage. Goldsworthy illuminates that it is the materials that hold the true value. Products are just vehicles for materials to flow through.

While designing pro-actively seems like the simplest solution, the reality of doing this in practice is far from simplistic. In addition, taking a sole focus on designing pro-actively leaves the current resources in our products (not designed pro-actively) as waste. This research, therefore, joins up the thinking to explore design strategies from both re-active and pro-active starting points. As Goldsworthy (2014:1) explains “although pro-active strategies are a key area for designers to develop, re-active approaches will continue to be needed to address the waste already in the system.

LIMITATIONS OF THE CURRENT DESIGN FOR RECYCLABILITY STRATEGIES

If the design challenge is to design textiles that can be recycled, we must first consider the strategies that exist to address this problem, namely mono-materiality. Mono-materiality is commonly described as the use of a single material type for a product. Whilst this approach was promoted throughout research in the 1990s, it was first brought into the mainstream by Braungart and McDonough's (2002) cradle-to-cradle theory. Maintaining 'purity of materials' (Fletcher 2008) removes the challenges of blends and allows materials to flow into specific fibre recycling systems.

There are many examples of designers exploring this space, for example on the Bio-Inspired Textiles research project (www.bioinpiredtextiles.com) in which Kapsali and Hall (2022) provide examples of designers (Richards, 2012; Scott, 2016) that use specific textile structure in mono-materials that have clever shape changing functions normally achieved using a mix of material, such as electronics. In another example, utilising materials from the technical cycle, Goldsworthy's (2012) PhD research explored polyester recycling streams for polymer or monomer level deconstruction (Harmsen, Scheffer and Bos, 2021). Here she used laser finishing techniques to create added aesthetics and function to polyester fabrics. This laser method avoided the addition of other materials to create a variety of textiles finishes which would otherwise leave the textiles difficult or impossible to recycle.

In the biological cycle, many design projects have experimented with the potential of biodegradable and compostable materials. These approaches often explore new production modes such as with Suzanne Lee's Biocouture cellulosic leather which is grown from bacteria and can be fully composted at the end of life (Tibbits, 2017). There is a growing research space for circular bio-based materials which includes for instance HereWear (https://herewear.eu/) and Bio-manufacturing Textiles from Waste (https://www.rca.ac.uk/research-innovation/projects/bio-manufacturing-textiles-waste/). These approaches are expanding as it become more critical that we find alternatives to fossil fuel-based materials and question the potential of bio-materials to replace our current over-use of plastics (Lee *et al.*, 2020).

Yet, despite the fact that blends are a barrier to a full transition to a circular economy, it seems unrealistic to expect material combinations to be eradicated entirely. Blends can offer many qualities and improve not only the technical but also the environmental performances of materials (Thackara, 2006). What is clear is there is a balance to be found between designing for function and recyclability. This is supported by the findings from the European Clothing Action Plan (ECAP, 2019) 'Fibre to Fibre' project. One of the trade-offs they found was the balance between creating a strong blended yarn that would be detrimental to recycling, or a pure but weaker recyclable one. In addition, ECAP emphasised the balance between aesthetics and technical design for recyclability. Design for Recycling often enforces a minimalist approach which, they point out, is not to everyone's taste. If combining materials was banned this might stunt creativity which is argued, by Forst (2019) to be an important part of the textile designer's remit.

Furthermore, promoting solely a mono-material approach could also be problematic. The textile industry already relies heavily on a small range of fibre types with cotton and polyester as the overwhelmingly predominant resources (EMF, 2017). In the light of possible resource scarcity and price fluctuation, a shift away from this monoculture should be encouraged. In light of this, blends can offer more variety. As resource availability becomes a challenge in our fast-changing world, using material combinations to spread the strain over different types of fibres could by a valid strategy for resilience. While mono-materiality offers a relatively direct path to material recovery and recycling, it also tends to limit the scope of materials that are used throughout the industry (Fletcher, 2008; Niinimäki, 2014) and seems to contradict the belief that sustainable design should also celebrate diversity (Benyus, 2002; Braungart and McDonough, 2002).

5. UNDERSTANDING BLENDS

For designers to understand how textile materials are blended, they must delve into technical texts and translate them for their needs. Blends are formed by bringing together different fibre types, and Hatch (1993) has examined five different ways in which this can be done:

1. Self-Blend or Mixture
2. Intimate Blend
3. Combination Yarn
4. Mixture Fabric
5. Compound Fabric

The first method brings together fibres to form a yarn, either using two or more of the same species of fibre to form what is referred to as a 'self-blend' (Hatch, 1993) or a 'mixture' (Sinclair, 2014). The second blends together different fibre types to form a 'intimate blend within a yarn', such as a yarn with two or more fibre types or a covered yarn. The third method of blending creates a 'combination yarn' which is achieved by the twisting together (or plying) of two different yarns (Hatch, 1993). The fourth blending method produces what Hatch calls a 'mixture fabric'; this might be created by the warp and weft in a woven textile being comprised of two different yarns. Alternatively, it could be created with two differing yarns in a knitted fabric, for example when creating stripes. Finally, it could also extend to embroidery techniques with a thread made from a different material, not explored by Hatch in her book. The fifth and final, blending approach is through the creation of a 'compound fabric' which Hatch (1993:372) describes as being "composed of two or more layers of fabric [or another component] .... held together by stitching, fusing, adhesive".

Further to this Forst (2020) adds a sixth method of blending to Hatch's typology, which involves combining textile materials during the construction of products. Such combinations of materials, she suggests, could occur when stitching a mono-material garment together with a different fibre sewing thread. Relevant to recycling, this could be extended to include the contaminants that are removed in the cleaning stages such as care labels and buttons made of different materials to the main fabric of the garment and therefore contributing to the overall blended composition.

BLENDING BY HIERARCHY

The first type of blending outlined in this research is the categorising of the different types of blending according to the textile hierarchy. This was established by Author1 in her PhD research (Hall, 2021) by studying the types of blending outlined by Hatch (1993) and Forst (2020). It quickly became apparent that the first three types of blending: self-blend or mixture, intimate blend and combination yarn all occurred during the creation of yarns, described as 'yarn level blending'. The fourth and fifth types of blending: mixture fabric and compound fabric occurring during the construction of fabrics/materials and thus is material level blending. Finally, with the addition of blending during the construction of products, this final category is simply described as product-level blending.

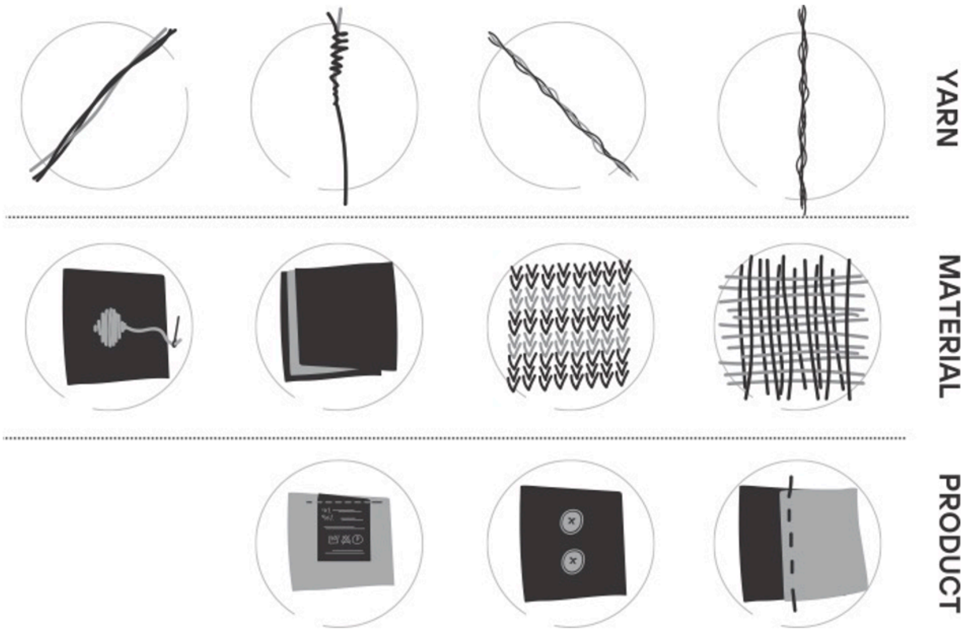

Figure 2. Blending by Hierarchy

Outlining these blending levels (illustrated in Figure 2) acts as a tool for designers to begin to understand how and where blending occurs. Designers often incorporate blending across these levels resulting in very complex blends, therefore, laying out a hierarchy can start unpacking the different types of blends which need to be addressed in a shift to circularity. If designers, are to design out blends to aid recyclability this is the first step in understanding where they occur and how design could be done differently.

BLENDING BY TECHNIQUE

Blending by hierarchy is the not the only way to understand blending. As we delve into the different methods designers use to combine materials the more complex it becomes. This complexity was investigated by Author2, in her PhD research (Forst, 2020) through the desire to communicate the challenge of textile blends to designers. In doing this she produced a variety of 'blown-up' textile structures representing the different ways our textile materials can be combined. Twenty 3D schematic representations of the most common encountered blends were produced by drastically enlarging the scale of the materials/yarn, that in the original textiles would be a fraction of a millimetre in diameter but is now, created using materials such as cord and foam in two contrasting colours to represent two different fibre types. This is not an exhaustive list of blending techniques. Rather they demonstrate a range of blending archetypes to represent the complexity and helps to pose the question: how can these combinations be reversed, and the stitches be undone, if the materials belong in different recycling processes?

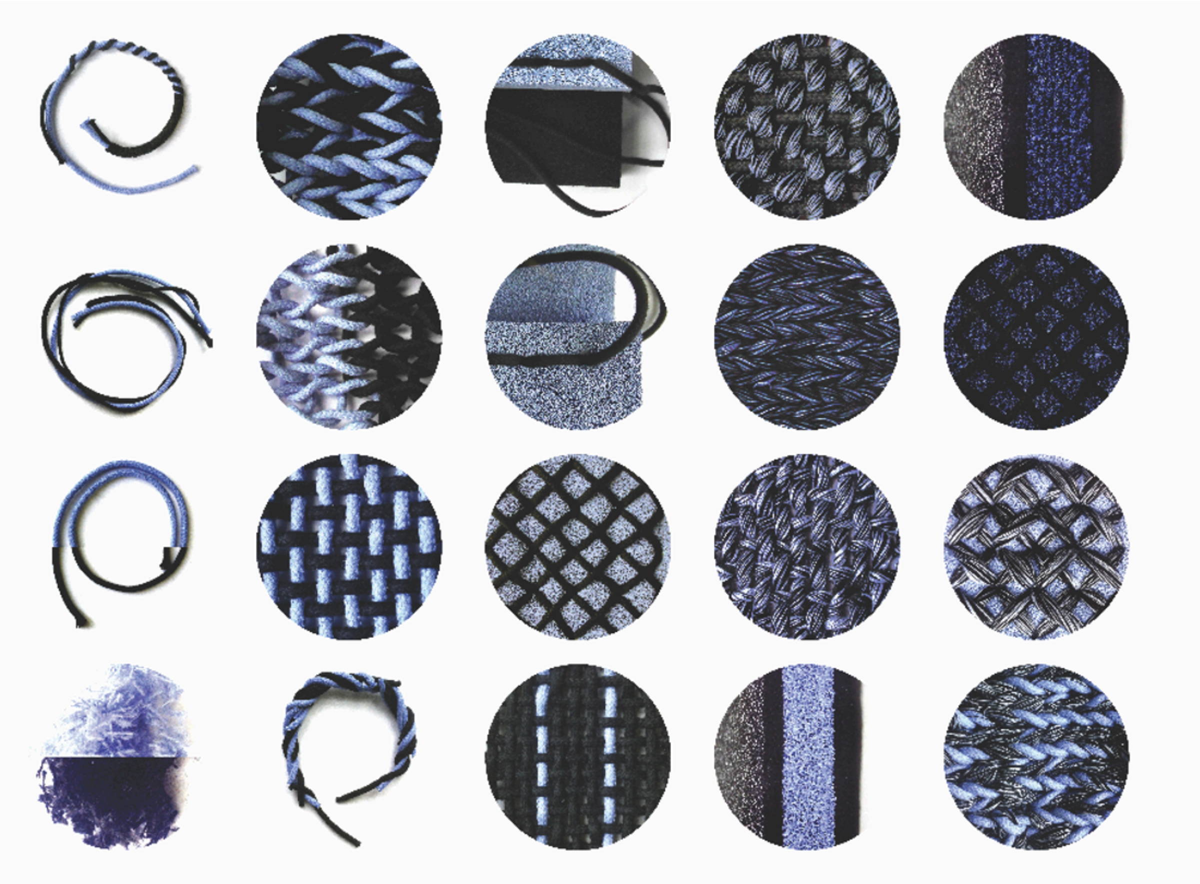

Figure 3. Twenty blend archetypes

These blend archetypes were subsequently mapped by Author2 into different levels according to technique complexity. Level 0, first demonstrates a mono material elements, such as fibre or yarn. Level 1, demonstrates techniques used to combine two mono-materials. Finally, level 2 describes combinations which are made of a mono-material and a blend (from Level 1 of two mono-materials), or two elements both made of a blend from Level 1. This is, again, not exhaustive and the levels could extended with numerous additional fibres types and combinations of techniques. For example, the next level would show blends made from a combination of level two blends and any another fibre type. At each level the number of stages of disassembly increases and therefore so does the complexity.

Since this first categorisation, by Author2, across level 0, 1 and 2, the techniques have been further divided in terms of their hierarchy by Author1. This iterative mapping of blends according to key characteristics gradually contributes to an understanding of blends that can suit multiple circular design practices. This enables the designer to easier understand how the two blending types (hierarchy and technique) interconnect (Figure 4).

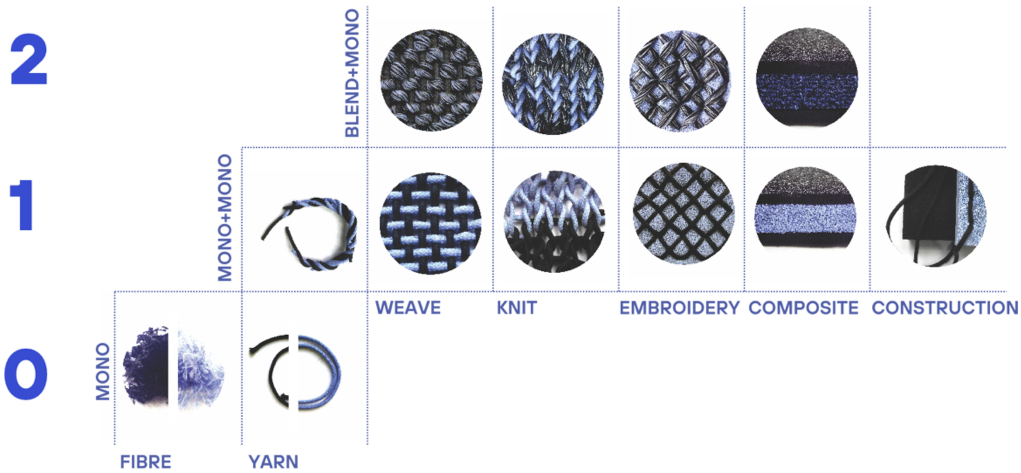

Figure 4. Blending by technique

The mapping and creation of the blending by technique builds on the blending by hierarchy model exploring the relationships between the different levels at which the combination of resources may occur and provide starting points for different solutions to be explored. These types of techniques that create blends and cause issues for recyclability is faced by the textile designer every day and outlining this aids their understanding of how blends have been created. For example, some blends, such as stripes in knits, may be pattern-led and focussed on the aesthetic qualities of materials, other more intimate blends such as yarns with a different material core may have a more function-focussed approach. Outlining these levels helps the designer to unpick how blending is conducted and offers a tool for designing blends in new ways for the circular economy.

BLENDING BY FIBRE TYPE

In the next part of the article, we look at the the specific types of fibres that could be blended. After setting out blending by hierarchy and technique this gap was established and blending by fibre type was explored. While there are a numerous different types of textile fibres available to the designer, three catagories of fibres type were selected to illustrate this and included, animal fibres (such as wool), vegetable fibres (such as cotton) and synthetic fibres (such as polyester). This meant that materials from both biological and technical spheres where also represented.

Blending was separated into five levels. Level 1 begins with a mono-material (no blend), such as only wool and is aptly named mono. This is followed, secondly, by subtle blends. This is a 'mixture' (Sinclair, 2014) of two similar fibres, such as merino wool and lambswool. Although this could also extend to two 'animal fibres' such as camel hair and wool. This type of blending doesn't necessarily cause concern to recycling processes but depending on the conditions of the recycling technology it has the potential to start to become problematic. Thirdly, blending is conducted within a single cycle and therefore is named cycle blending. Figure 5 illustrates a blend within the biological sphere, such as wool and cotton, but could also be created by a blend in the technical sphere, such as polyester and nylon. Whilst this type of blending fulfils the circular economy and cradle-to-cradle conditions of separating resources by sphere or cycle these blends cause more significant problems for recycling technologies. The fourth level simply describes the blends that were coined as 'monstrous hybrids' (Braungart and McDonough, 2002) combining fibre types from either biological and technical cycles. These are named hybrid blends. Finally, level 5 climaxes with the most complex of blends (described simply as complex blends), combing materials from all their categories animal, vegetable and synthetic.

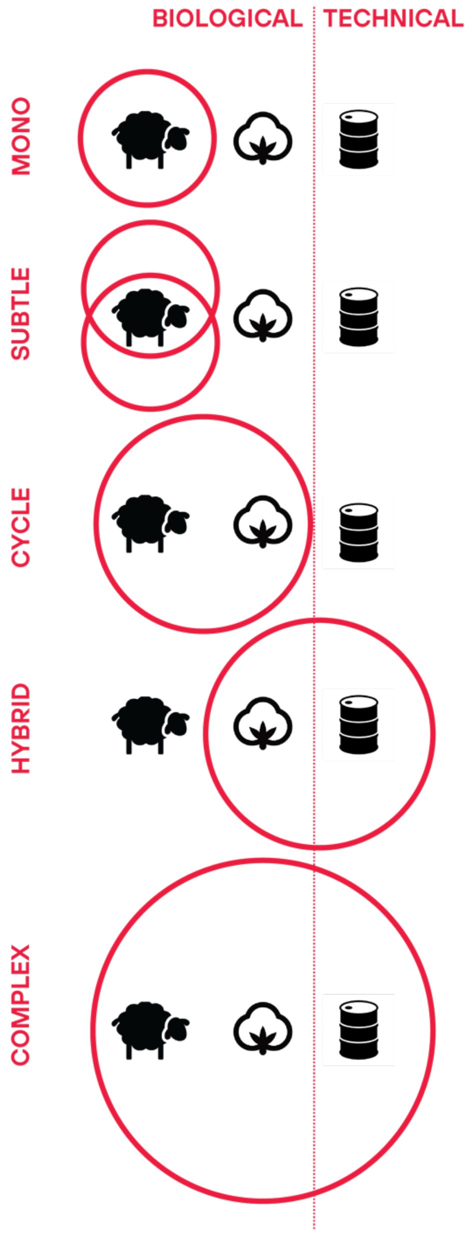

Figure 5. Blends by Fibre Type

There are obvious benefits to explaining blending in these terms for designers and when combined with an in-depth knowledge of recycling systems this tool becomes even more valuable. This also expands the two previous blending categories by providing context and complexity. By understanding the vast array of fibre types that could be combined and what this means the textile designer can then pinpoint the way blending has been conducted (blending by technique) and where it is conducted (blending by hierarchy).

UNDERSTANDING BLENDS IN PRACTICE

Having explored the different types of blending this research sets out to demonstrate how this knowledge can be used in practice. The next two sections explore example from Author2's (Forst, 2020) and Author1's (Hall, 2021) PhD practice research studies to demonstrate how elements of the models below can be harnessed to design blending for a circular economy. Specifically, Author2 explores a pro-active approach to designing blends for recyclability, and Author2 explores re-active approaches addressing the same problem through completely different means.

6. PRO-ACTIVE: TEMPORARY BLENDS

With a strong understanding of the various blend and assembly types, designers are in a position to propose alternative pro-active methods which provide similar benefits to 'monstrous hybrids' but circumvent the issues they pose to recycling. The research put forward in this case study draws on the established principles of design for disassembly, prevalent in industrial product design under extended producer responsibility (EPR) regulation and adapts it to the challenge of blends in textiles. In this case, the understanding of blend hierarchies, techniques and types is geared toward a redesign of blends and proposing new ways of assembling resources so that they can deliver expected aesthetic and technical properties but still be taken apart and returned to a mono-material or at least recyclable component at end of life.

Design for disassembly is defined as "a characteristic of a product's design that enables the product to be taken apart at the end of its useful life in such a way that allows components and parts to be reused, recycled, recovered for energy or, in some other way, diverted from the waste stream." (International Organization for Standardization, 2016). Using textile design knowledge, conventional assembly techniques in weaving, embroidery, or felting were modified to enable later disassembly of the parts made from materials belonging in different recycling streams. In this way a range of techniques for the temporary assembly of textile components in ways which enable recovery and recycling at end of life were developed. These can be used as models for other designers to take on in textile or fashion design practice and support a shift to circularity.

THE CHALLENGE: ELASTIC AND LAMINATION

Based on an early assessment through literature review and interviews of the main challenges for textile recyclers when addressing blends, it was found that two main problem materials emerged. Laminated or coated textiles prevent the easy and automated detection of material types (for example in the emerging field of near infrared sorting) and disagree with the machines shredding textiles for mechanical recycling. Similarly, stretchy textiles including elastane are a well-known barrier to effective recycling as the elastane fibre is difficult to recycle mechanically or chemically (Östlund *et al.*, 2017). These two textile types, which were represented in the enlarged blend models introduced as part of the review of blend types, laminated/coated, and stretchy, were used as a starting point to emulate the properties of common problematic blends through textile design for disassembly. The various techniques and illustrative textile samples produced in this research offer a range of ways of approaching these functions while still allowing for end-of-life disassembly, recovery, and recycling of the components. While the textile design for disassembly demonstration samples differs in technical and aesthetic properties from conventional laminated or stretchy materials, they aim to represent an alternative to short-sighted blending in textiles. Alongside a new way of thinking about material combination, this approach heralds a new form of aesthetics which are driven by environmental considerations rather than a designer's aesthetic preferences alone. In this sense, circular design constraints are seen as a creative trigger rather than a limit.

TYPES OF BLENDS ADDRESSED

In combination with the blend qualities that were selected for redesign, the research focussed on a range of blend types as defined in the classification exercise.

Blending by Hierarchy - Material and Product Level:
The scope of this exploration of textile design for disassembly addressed the types of blends that could be identified as the remit of a creative textile designer, that is blends in which the assembled elements can be seen as contributing individually to the aesthetic, for instance, a stripe in a knit, or an appliqué fabric. The hierarchy of blend is therefore addressed at the material or product level rather than at the yarn level in which the elements are more subtle.

Blending by Technique – Mono + Mono:
To best represent the concept of design for disassembly at a textile scale, the simpler blending level 1 was addressed rather than level 2 which already embeds blends within blends. The aim of the disassembly feature is therefore to return from a level 1 blend to the level 0 mono-material elements. The level of blending is addressed through all techniques from weave to construction, therefore only excluding fibre blending to produce a yarn.

Blending by Fibre Type – Hybrid Blend:
Although the experimental samples were made with placeholder materials, this type of approach is intended primarily to address hybrid blends or 'monstrous hybrids' that combine resources from different cycles. In later stages of the development of the techniques, it could be considered to redesign complex blends through textile design for disassembly, but in this exploration the binary approach of hybrid blends is the focus.

FOUR TYPES OF TEXTILE DESIGN FOR DISASSEMBLY

Through creative textile design practice, a range of samples were made to demonstrate assembly for disassembly techniques at the scale of fibres through needle felting, at the scale of yarns with weaving, and at the scale of fabric components with laser cutting and hand assembly. The samples attempt to emulate effects of stretch or lamination while embedding the principle of disassembly. This leads to new functional and aesthetic properties where some elements are externalised as a detachable surface element rather than mixed into the yarns of the textile. The scale at which components are assembled is also different to conventional blends in the laser cut samples with layers of fabric intermeshing to produce a simile to laminated materials. In each sample a conventional textile technique is adapted to the disassembly brief and modified in line with a new, circular, vision for textile blends.

Through reflective review the samples were identified as representing four separate techniques: Light connections (felted layers), redundant thread (woven structure), dovetail (laser cut elements), textile lock (3 part laser cut and assembled structure). Together they form a repertoire of techniques that can be adapted in textile and fashion design practice by others.

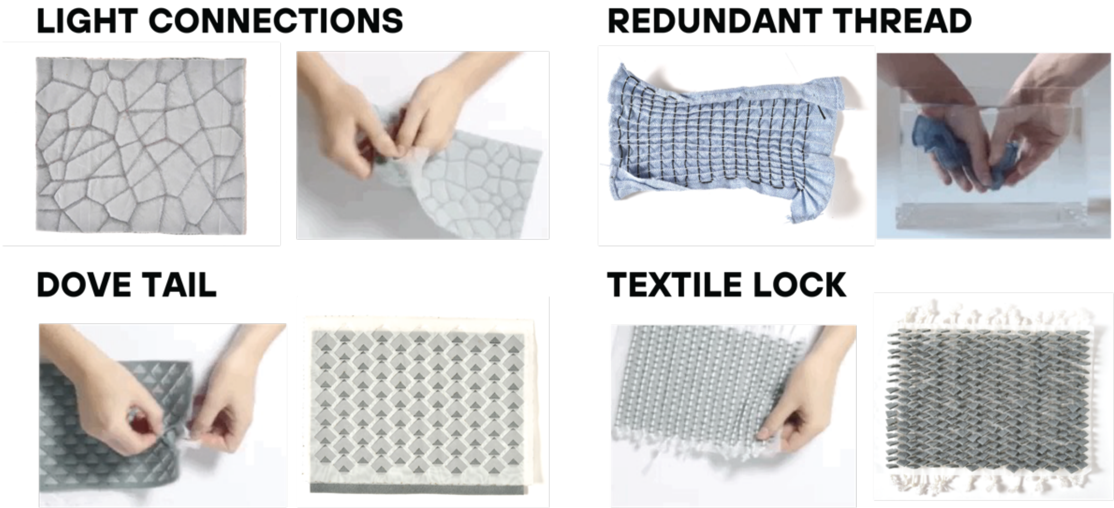

Figure 6. Light Connections, Redundant Thread, Dovetail and Textile Lock (Forst, 2020)

The light connection technique was developed by felting two layers of fabric together, needle punching the long and loose fibres of a non-woven, which could provide heat insulation, through a tightly woven canvas, which provides some water-resistance. The pattern that can be seen on the surface are the lines that connect the two materials. It is sufficiently robust to hold the layers together during the product lifetime, but the top layer can be peeled away by hand to separate the materials at end of life. This is a destructive disassembly which cannot be reversed.

In the redundant thread technique, an additional thread is laced between the base layer and the functional element, either an elastic thread or a special covering ribbon, to connect them while not contributing directly to the core structure of the weave, so that when it is removed through dissolution, the base layer remains whole. This is also a non-reversible disassembly although the base can be still useable in further applications before end-of-life recycling.

The dovetail assembly technique is closely related to wood assembly approaches which provided inspiration for these textile samples. The aim is to interlace layers of fabric to cover a bases with a mesh or tiling effect, conferring properties such as water-resistance or breathability. The diamond shaped cut-outs are inserted through slits in a base layer to join the elements. This technique is reversible, leading to a more playful or modular approach to disassembly which could reach beyond end of life recycling into lifecycle extension strategies.

The textile lock technique functions in a similar way to the dovetail assembly but uses a third element to lock two layers of fabric together. This means that the integrity of the layers can be maintained to a greater extent and provide more conventional functionality. This is also a reversible assembly and disassembly technique which can be effected at various moments of the products life. This is the technique that was selected to carry through at the product scale.

Each of these textile design for disassembly techniques demonstrates an understanding of how conventional blends are produced with techniques like fusing, intimate fibre blending, embroidery and stitching, etc, and proposes an alternative to assemble resources in temporary ways.

PRODUCT LEVEL: THE SPLIT JACKET

To test the concept and techniques of textile design for disassembly in context, a garment using one of the new assembly techniques was made. This garment, the Split jacket, is an assemblage of two materials from different cycles. The outer layer is made of biodegradable leather, while the lining is made of a recycled polyester. The two parts are laser cut and then hand assembled in a way that the inner layer sits slightly away for the outer and creates an air pocket between the two, thus conferring some comfort properties through the design for disassembly technique. Jackets are generally complex garments that cause issues when it comes to recycling as they are made of multiple materials and trims. Here, the parts can all be taken apart by hand in order to recycle or repair the garment. While the design for disassembly technique was developed at a material level, in the garment it operates at a product construction level, bringing together the outer and the lining but also the sleeves, collar, and body of the garment. Finally, although not conducted in this research, this approach could also be applied to recycled or waste materials. The emphasis of this approach is on the future recyclability of the design created.

Figure 7. The Split Jacket, (Forst, 2020)

7. RE-ACTIVE: RECYCLED BLENDING

At the other end of the spectrum the knowledge of blending outlined in this paper also provides designers with the tools to find solutions for the complex waste that already exists using re-active methods. For this, knowledge about recycling systems and streams holds the key. The case study below specifically focuses on mechanical recycling technology which recycles textiles to produce fibres (Harmsen, Scheffer and Bos, 2021). This process cannot separate fibre blends that already exist, unlike other types of recycling.

While mechanical or fibre level recycling is often seen as outdated because it was invented over a century ago (Allwood *et al.*, 2006), this technology is still the most relevant for textile fibres such as wool (and acrylic, the focus of this study) evidenced by investiment into wool recycling such as iinouiio (UKFT, 2022). There are, of course, limitations to this process. The act of teasing the fibres from the cloth results in breakages and therefore the recycled fibres become shorter. To overcome this, when the recycled fibres are remanufactured, blending is used for many reasons such as combining longer, stronger fibres to support the shorter, weaker recycled ones. Blending, therefore, is used as a design tool in both the manufacture of virgin and recycled fibres.

THE CHALLENGE OF WOOL/ACRYLIC

Acrylic fibre is closely connected to the production of wool and therefore also to the recycling of wool textiles. This is due to many of its attributes mimicking wool's properties (Hatch, 1993) and is commonly used in the knitted apparel industry gaining popularity because when blended with wool it can reduce cost (Sinclair, 2014). The accumulation of cheap acrylic knitwear and its blends is a mounting resource but this fibre, that has already been produced, should not be wasted but requires considerable thought regarding its application. The combination of wool and acrylic fibres, by default, at the end-of-life contaminates wool recycling streams. The blends between wool and acrylic are present across the global wool recycling industries including the lowest grades in Prato, Italy (Hall, 2018).

If we are to design for mechanical textile recycling systems, that cannot separate these blends, we must understand how the industry currently sorts these materials. Sorting categories between wool and acrylic knits were established through an assessment of the literature available and interviews with a sorter and recycler both working in the wool recycling industry in Pakistan and Italy respectively (Hall, 2021). Four sorting grades were established from the high value 100% wool, through the middle value grades, 80% wool and 50% wool and ending finally in the lowest value 0%wool/100% acrylic. Although these grades were identified they are shrouded in complexity. For example, the names of these grades, such as 50% wool, does not necessarily represent the percentage of wool an individual textile in the grade or the overall batch of sorted textiles will contain. They could contain less wool than the name suggests. This also means that the 100% wool or 100% acrylic grades are not completely pure. Furthermore, any of these grades could also contain other fibre types outside of wool and acrylic. Therefore, these grades are represented by blurry boundaries and thresholds that suggest the lower and upper percentages of wool that might be accepted for each grade.

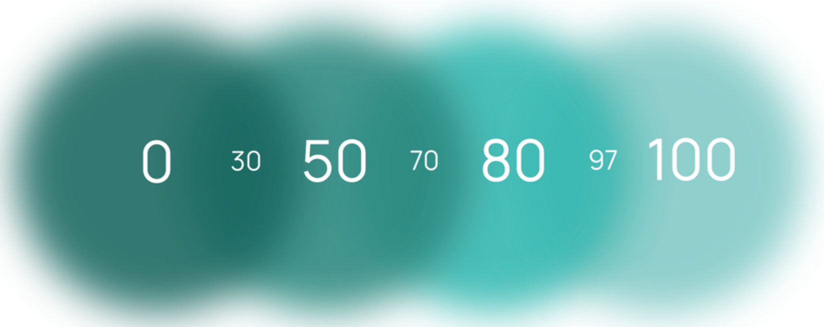

Figure 8. Wool/acrylic sorting grades and thresholds visualised to represent the blurred boundaries between the sorting categories (Hall, 2021).

TYPES OF BLENDS ADDRESSED

Within the scope of wool/acrylic mechanical textile recycling, the research focussed on a specific range of blend types as defined across the classifications in this paper.

Blending by Fibre Type – Complex Blend:

With the sorting categories establish the research focussed on the lowest value grade 100% acrylic. As discussed above, while this may sound as if this only contains acrylic fibres the reality is that it could contain any number of fibre types, even wool. This, therefore, is a complex blend, that without scientific testing (which is expensive and time consuming to conduct on every batch of textiles), the composition can only be assumed to be a majority of acrylic.

Blending by Technique – Blend + Mono:
While the focus of this research is on knitted textiles this also includes a wide range of blending techniques within knitwear, which include knitting numerous ways, such as stripes, intarsia or Fair Isle to name only a few, a range different yarns, blended and mono.

Blending by Hierarchy - Yarn Level:
One of the many challenges for fibre level recycling is the route to application of recycled fibres. The traditional route takes knitted or woven textiles and recycles them into either woven or non-woven materials. Normally these woven and non-woven textiles are used in interiors or architecture and not garments. As expert wool sorter Hasnanin Lilani explains, recyclers "prefer the knits" because of their loftier more open structures making the fibres easier to tease from the cloth. "They are using knit material and turning it into woven" Lilani explains (Hall, 2021:280), meaning that the route from knitted textiles back into yarns for knitwear has been underexplored.

YARN LEVEL: BLENDING RATIOS

When dealing with waste textiles, there is less concern for pinpointing precisely where blending has occurred. It matters little to a recycler (unlike the designer) if blending happens across the hierarchy at yarn, material or product level or which technique has been used, the blended garment is still ultimately a blend. Rather, it is the ratio of the blend fibre type that is the priority.

However, for the designer, it is vital to understand how the decisions made across the blending hierarchy and technique affect this ratio and what this will means for the garment in the recycling system. For example, at yarn level two fibres are blended for cost, such as 50% wool and 50% acrylic. This is then knitted into a fabric with a stripe of equal size for aesthetic reasons, made from an 100% wool yarn. Blending occurs at both yarn and material level, however, the most relevant for recycling is the blending at material level. This has not contaminated the blend any further as the yarn was already made of both wool and acrylic. It has merely increased the ratio of wool within the blend. For the designer the choice to increase or decrease a blend ratio can happen at any level.

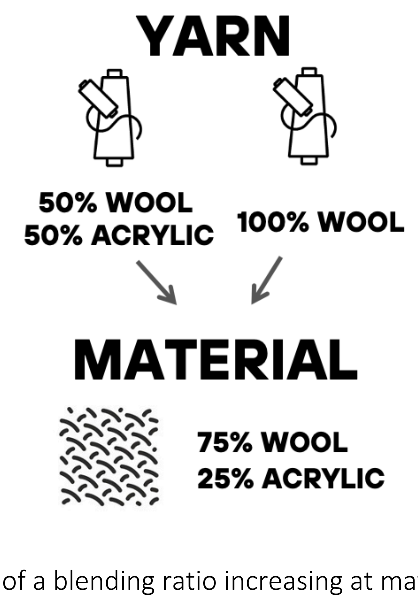

Figure 9. An example of a blending ratio increasing at material level

INCREMENTAL BLENDING

How can the designer harness this understanding of blend ratios towards a re-active design approach? The answer can be found in an incremental approach which was proposed by Carlsson *et al.* (2017). This suggests that the designer can incrementally update garments to extend their lives but has been reframed for this context of developing yarns from recycled fibres. If we start with the lowest value grade (100% acrylic), then it follows that value can be added by blending this fibre with wool. The value referred to here is specifically then value when it re-enters waste streams and is once again sorted. For example, blending the 100% recycled acrylic with 50% virgin wool (to support the shorter acrylic fibres) would create a new yarn/material that during the sorting (in recovery) would enter a new sorting grade - the higher value 50% wool.

This strategy, of incremental blending combined with blending ratios, has the potential for the designer to create resource (fibre) longevity. As Roos *et al.* (2019) explains adding a percentage of recycled fibres in all fabrics provides an opportunity to increase the use of recycled fibres and thus extend their lifetimes. Therefore, if the designer can use blending to not only extend the life of a fibre but also the value of the fibres in recovery then these fibres can circulate in the system for even longer.

PRODUCT LEVEL: DESIGN FOR RECYCLING KNITWEAR

Although this research has focused mainly on yarn level, the same thinking must also be applied by the designer across the hierarchy at material and product levels. Blending by technique also plays into the blend ratios, as not only can textile designers create patterns with multiple yarns within a jumper, but blending can be employed during garment construction, such as linking garment pieces with a new thread and adding elements such as care labels.

To explore how these blends are designed controlling the blend ratio, a jumper was created. The yarn used was a 50/50 blend between recycled acrylic and wool, however, blending at material level was intentionally design out with a simple one yarn construction. As the jumper was not made commercially, care and brand labels were not required as part of the design, but the act of creating the jumper highlighted where these possible blends would take place and provides a challenge for future research. Finally, although this approach is focused on re-active design the lessons learned from sorting and blend ratios could also be applied to pro-active design.

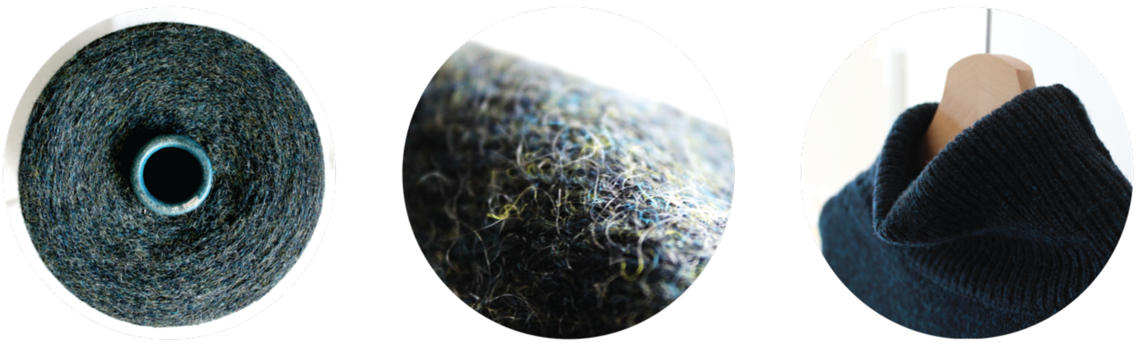

Figure 10. Yarn, knitted fabric and roll-neck jumper designed using blending ratios for resource longevity in the mechanical wool/acrylic recycling system, (Hall, 2021)

8. CONCLUSIONS: DESIGNING TEXTILES IN COMPLEX SYSTEMS

This paper explores the complex landscape of textile blending through an after-action review method (Morrison and Meliza, 1999) of two doctoral research studies (Hall, 2021; Forst, 2020) focused on finding solutions to challenges that blending provides for recycling in the circular economy.

Comparing the mapping the research three ways to understand blending emerged. First blending by hierarchy pinpoints the exact position of the blend with the textile hierarchy, such as yarn, material or product level. Second blending by technique builds on this approach by incorporating the textile methods, such as, covered yarn, knitted stripes or embroidery added to a fabric. The complexity is increased by the number of new materials incorporated within the techniques, such as a mono yarn combined in a woven fabric with another mono yarn or a blended yarn knitted into a stripe with a mono yarn. Finally, blending by fibre type provides the material context for the blend and offers a way to understand how different resources (animal, vegetable, synthetic) can be combined. This occurs as first a subtle combination, such as two different animal fibres. Secondly, a cycle combination blending fibres within either the biological or technical cycle. Thirdly, hybrid blends, combining resources from both biological and technical flows. Finally, a complex blend, combining resources from all three fibre groups and beyond.

The two case studies (from the two PhD studies) demonstrated two different approaches to applying the understanding of blends in practice. First Author2 investigated a pro-active approach (Goldsworthy, 2014), which designs blends from the start so that they can be separated. In this case a focus on textile design for disassembly was taken. The case study demonstrated an alternative way to design hybrids blends, at material/product level using techniques that combined two different mono materials together. The final fabric and products combined materials from different cradle-to-cradle cycles that could be separated. This approach pro-actively, using craft methods, provides the designer with a way to combine resources to support rather than hinder a shift to a circular economy.

Second, Author1 explored the opposing method of re-active design (Goldsworthy, 2014) designing from the point of disposal using materials and their blends that already exist. This case study demonstrated methods to extend the life of complex blends, at yarn level using techniques that combine blends and other materials together. Focusing on designing yarns for knitted textiles from the complex knitted waste that is sorted for mechanical textile recycling systems, the importance of blending ratios was unpacked. For the designer, how the different blend techniques and fibre types combine and at which level in the hierarchy is the key to establishing and controlling through design the final blend. This re-active approach, using industrial based methods, provides the designer with a way to use blending to support resource longevity and keep them circulating in the economy.

The comparison between these two case studies makes clear that blending and recovery are not mutually exclusive. Mono-materiality as a strategy is not the only way that textile designers can solve the challenge of blends for recycling systems. It is vital for textile designer to look at the whole picture to find solutions, considering pro-active design and re-active ones in addition to mono-material strategies is the only way that we can start to find solutions to all our needs in the circular economy. We conclude that textile blends can, with forethought, form part of the circular economy.

9. REFERENCES

Allwood, J.M. *et al.* (2006) *Well dressed? the present and future sustainability of clothing and textiles in the United Kingdom*. Cambridge: University of Cambridge, Institute for Manufacturing.

Arnheim, R. (1969) *Visual thinking*. Berkeley: University of California Press.

Benyus, J.M. (2002) *Biomimicry: Innovation Inspired by Nature*. New York, NY: Harper Perennial.

Beton, A. *et al.* (2014) *Environmental improvement potential of textiles (IMPRO Textiles).* Luxembourg: Publications Office. Available at: http://dx.publications.europa.eu/10.2791/52624 (Accessed: 13 November 2018).

Braungart, M. and McDonough, W. (2002) *Cradle to Cradle. Remaking the Way We Make Things*. 1st Edition. New York: North Point Press.

Carlsson, J. *et al.* (2017) *Feasibility of conditional design Organizing a circular textile value chain by design principles*. Gothenberg Sweden: University of Borås,. Available at: http://hb.diva-portal.org/smash/record.jsf?dswid=9502&pid=diva2%3A1362431&c=29&searchType=RESEARCH&language=en&query=&af=%5B%5D&aq=%5B%5B%7B%22personId%22%3A%22rpa%22%7D%5D%5D&aq2=%5B%5B%5D%5D&aqe=%5B%5D&noOfRows=250&sortOrder=dateIssued_sort_desc&sortOrder2=title_sort_asc&onlyFullText=false&sf=all (Accessed: 6 January 2020).

Dormer, P. (1997) *The culture of craft*. UK ed. edition. Manchester, UK ; New York, NY : New York: Manchester University Press.

van Duijn, H. (2019) *Fibersort: Potential Barroers for long term implementation of the Fibersort*. Amsterdam : Netherlands, p. 8. Available at: https://www.nweurope.eu/media/6811/fibersort-barriers-report-final.pdf (Accessed: 31 October 2022).

Dutch Clothing Mountain (2017) *Measuring the Dutch clothing mountain: Data for sustainability-oriented studies and actions in the apparel sector*. Amsterdam: Hogeschool van Amsterdam. Available at: http://www.hva.nl/create-it/gedeelde-content/projecten/projecten-fashion/measuring-the-dutch-clothing-mountain.html (Accessed: 13 February 2018).

ECAP (2019) *Design Factsheet*. Amsterdam, Netherlands: Rijkswaterstaat: Ministry of Infrastructure and the Enviroment. Available at: http://www.ecap.eu.com/take-action/fibre-to-fibre/ (Accessed: 10 April 2020).

Ellen MacArthur Foundation and IDEO (2017) *The Circular Design Guide*. Available at: https://www.circulardesignguide.com/ (Accessed: 4 October 2018).

EMF (2013) *Towards the circular economy: Economic and business rationale for an accelerated transition*. 1. London: Ellen Macarthur Foundation, pp. 23–44. Available at: https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf (Accessed: 1 June 2019).

EMF (2017) *A New Textiles Economy: Redesigning Fashion's Future*. London: Ellen Macarthur Foundation and Circular Fibres Initiative. Available at: https://www.ellenmacarthurfoundation.org/assets/downloads/publications/A-New-Textiles-Economy_Full-Report.pdf (Accessed: 3 January 2018).

Fibersort (2018) *Fibersort Reference Sheet*. Interreg North-West Europe. Amsterdam, The Netherlands: Circle Economy. Available at: https://www.circle-economy.com/fibersort-industry-reference-sheet (Accessed: 8 January 2020).

Fletcher, K. (2008) *Sustainable Fashion and Textiles: Design Journeys*. 1 edition. London ; Sterling, VA: Routledge.

Forst, L. (2019) 'Disassembly Discussed: Creative Textile Sampling as a Driver for Innovation in the Circular Economy', *Journal of Textile Design Research and Practice*, 0(0), pp. 1–21. Available at: https://doi.org/10.1080/20511787.2019.1667156.

Forst, L. (2020) *Textile Design for Disassembly: A creative textile design methodology for designing detachable connections for material combinations*. PhD Thesis. University of the Arts London.

Goldsworthy, K. (2012) *Laser-finishing: a new process for designing recyclability in synthetic textiles*. PhD Thesis. University of the Arts London. Available at: http://ualresearchonline.arts.ac.uk/11638/ (Accessed: 31 January 2018).

Goldsworthy, K. (2014) 'Design for Cyclability: pro-active approaches for maximising material recovery', *Making Futures*, 3. Available at: https://ualresearchonline.arts.ac.uk/id/eprint/6871/3/goldsworthy__kate_paper.pdf (Accessed: 3 October 2017).

Hall, C. (2018) 'MIXING IT UP IN PRATO: identifying innovation hotspots within mechanical textile recycling', in *Global Fashion Conference*. *What's Going On? A discourse on Fashion, Design and Sustainability*, London: GFC 2018. Available at: https://docs.wixstatic.com/ugd/eb22a2_4a7b43538fbf45a7bc753a8a8bfb6aad.pdf (Accessed: 31 May 2019).

Hall, C.A. (2021) *Design for Recycling Knitwear: a framework for sorting, blending and cascading in the mechanical textile recycling industry*. PhD Thesis. University of the Arts London. Available at: https://tinyurl.com/DesignForRecyclingKnitwear.

Hardingham, M. (1978) *Illustrated dictionary of fabrics*. London (etc.): Studio Vista.

Harmsen, P., Scheffer, M. and Bos, H. (2021) 'Textiles for Circular Fashion: The Logic behind Recycling Options', *Sustainability*, 13(17), p. 9714. Available at: https://doi.org/10.3390/su13179714.

Hatch, K.L. (1993) *Textile science*. Minneapolis/Saint Paul: West Publishing Company.

Igoe, E. (2010) 'The tacit-turn: textile design in design research', *Duck Journal for Research in Textiles and Textile Design*, 1, pp. 1–11.

Igoe, E. (2021) *Textile design theory in the making*. London: Bloomsbury.

International Organization for Standardization (ed.) (2016) *Environmental labels and declarations - self-declared environmental claims (type II environmental labelling) =: Marquage et déclarations environnementaux - autodéclarations environnementales (étiquetage de type II)*. Second edition (2016-03-15). Geneva, Switzerland: ISO.

Kapsali, V. and Hall, C. (2022) 'Sustainable approaches to textile design: Lessons from biology', in *DRS2022 Conference Proceeding*. *DRS2022: Bilbao, 25 June - 3 July*, Blbao, Spain. Available at: https://dl.designresearchsociety.org/drs-conference-papers/drs2022/researchpapers/20.

Kaszynska, P., Kimbell, L. and Bailey, J. (2022) 'Practice research in design: Towards a novel definition. Social Design Institute Working Paper.', *London: University of the Arts London* [Preprint].

Lee, S. *et al.* (2020) *UNDERSTANDING 'BIO' MATERIAL INNOVATIONS: a primer for the fashion industry*. Lonodn, UK: Biofabricate and Fashion for Good. Available at: https://reports.fashionforgood.com/wp-content/uploads/2020/12/Understanding-Bio-Material-Innovations-Report.pdf.

Manovich, L. (2011) 'What is visualisation?', *Visual Studies*, 26(1), pp. 36–49. Available at: https://doi.org/10.1080/1472586X.2011.548488.

Mathews, B. (2015) *Closing the loop: an essential guide for the global textile supply chain*. Normanton, England: MCL Global.

Morrison, J.E. and Meliza, L.L. (1999) *Foundations of the After Action Review Process*. IDA/HQ-D2332. INSTITUTE FOR DEFENSE ANALYSES ALEXANDRIA VA. Available at: https://apps.dtic.mil/docs/citations/ADA368651 (Accessed: 19 June 2019).

Niinimäki, K. (2014) 'Sustainable Fashion: New Approaches'. Available at: https://www.academia.edu/68551167/Sustainable_Fashion_New_Approaches (Accessed: 22 October 2022).

Östlund, A. *et al.* (2017) *Re:Mix - Separation and recycling of textile waste fiber blends*. RISE Research Institutes of Sweden.

Papanek, V.J. (1995) *The green imperative: ecology and ethics in design and architecture*. London: Thames and Hudson.

Richards, A. (2012) *Weaving Textiles That Shape Themselves*. Illustrated edition. Ramsbury Marlborough, Wiltshire: The Crowood Press.

Roos, S. *et al.* (2019) *White paper on textile recycling*. 2019:09. RISE IVF AB: Mölndal, Sweden, p. 58. Available at: http://mistrafuturefashion.com/wp-content/uploads/2019/10/S.-Roos.-White-paper-on-textile-recycling.-Mistra-Future-Fashion.pdf (Accessed: 6 January 2020).

RSA (2016) *LESSONS FROM THE GREAT RECOVERY 2012-2016*. Available at: http://www.greatrecovery.org.uk/resources/new-report-lessons-from-the-great-recovery-2012-2016/ (Accessed: 14 November 2017).

Schön, D.A. (1983) *The reflective practitioner: how professionals think in action*. London: Temple Smith.

Scott, J. (2016) *Programmable knitting*. Ph.D. University of the Arts London. Available at: https://ualresearchonline.arts.ac.uk/id/eprint/18761/ (Accessed: 22 October 2022).

Sinclair, R. (2014) *Textiles and fashion: materials, design and technology*. Boston, MA: Elsevier.

Thackara, J. (2006) *In the Bubble: Designing in a Complex World*. Cambridge, UNITED STATES: MIT Press. Available at: http://ebookcentral.proquest.com/lib/ual/detail.action?docID=3339780 (Accessed: 6 April 2020).

Tibbits, S. (ed.) (2017) *Active Matter*. Illustrated edition. Cambridge, MA: The MIT Press.

Tufte, E.R. (2006) *Beautiful evidence*. Cheshire, Conn: Graphics Press.

UKFT (2022) *Camira Group takes majority stake in textile recycling business iinouiio*, *UKFT*. Available at: https://www.ukft.org/camira-iinouiio/ (Accessed: 14 November 2022).

Webster, K. (2017) *The circular economy: a wealth of flows*. Second edition. Cowes, Isle of Wight: Ellen MacArthur Foundation Publishing.