Check for updates

RESEARCH ARTICLE

Design for sorting knitwear: Exploring blended textile wastes and the relationship between sorting, recovery, and recycled blending in yarn manufacture [version 1; peer review: 2 approved]

Cathryn Anneka Hall, Kate Goldsworthy, Rebecca Earley

Centre for Circular Design, University of the Arts London, London, UK

v1 **First published:** 15 Nov 2022, **1**:3
https://doi.org/10.12688/materialsopenres.17478.1
Latest published: 15 Nov 2022, **1**:3
https://doi.org/10.12688/materialsopenres.17478.1

Abstract
Background: The problem of difficult-to-recycle textile waste is an ongoing challenge. One of the issues is the lack of exchange between the recovery sector and design/manufacture of recycled materials. This paper seeks to addresses the gap in knowledge between sorting (in recovery) and blending activities (in manufacture), expanding current design strategies towards textile recovery. To achieve this, the research explores sorting practices of wool/acrylic blends in the mechanical wool recycling industry and applies this knowledge to the design of new yarns.
Methods: A bricolage of methods was used to conduct this research in three parts. First, an overview of a previous study by Author1 is presented from which this research builds. Second, field research using conversation methods with the owner of a closed wool recycling company was conducted centring around their material archive. Thirdly, practice research was conducted in a spinning facility where Author1 applied knowledge from part 1 and 2 by designing four recycled yarns. This was supported by interviews with a sorter and recycler to expand on the findings.
Results: Four methods of sorting and the sorting grades/thresholds that are found in the wool recycling industry are outlined, and five methods of recycled blending historically used in the wool recycling industry are established. This knowledge (sorting methods/grades and recycled blending techniques) were applied in practice and from the methods employed, the relationship between sorting in recovery and recycled blending in manufacture was established across three themes: fibre quality, fibre type and fibre colour.
Conclusions: The paper concludes that understanding the link sorting and blending provides the foundations for a 'Design for Sorting' methodology. When lessons from each theme (quality, type and colour) are combined, this enables fibre value to be retained in

Open Peer Review

Approval Status ✔ ✔

	1	2
version 1 15 Nov 2022	✔ view	✔ view

1. **Kirsi Niinimäki**, Aalto University, Espoo, Finland

2. **Claire Lerpiniere**, De Montfort University, Leicester, UK

Any reports and responses or comments on the article can be found at the end of the article.

recovery and thus, provides a route for longevity of our textile fibres.

Keywords
Textile Recycling, Sorting & Blending, Recycled Wool & Acrylic, Design for Sorting, Circular Economy

This article is included in the Designing Materials for a Circular Economy collection.

Corresponding author: Cathryn Anneka Hall (cathryn.hall@arts.ac.uk)

Author roles: Hall CA: Conceptualization, Investigation, Methodology, Writing – Original Draft Preparation; **Goldsworthy K**: Supervision, Writing – Review & Editing; **Earley R**: Supervision, Writing – Review & Editing

Competing interests: No competing interests were disclosed.

Grant information: This research was financially supported by University of the Arts London PhD studentship award and a grant from Textile Cotton Research Trust. All funding was assigned to Cathryn Anneka Hall.
The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

How to cite this article: Hall CA, Goldsworthy K and Earley R. **Design for sorting knitwear: Exploring blended textile wastes and the relationship between sorting, recovery, and recycled blending in yarn manufacture [version 1; peer review: 2 approved]** Materials Open Research 2022, **1**:3 https://doi.org/10.12688/materialsopenres.17478.1

First published: 15 Nov 2022, **1**:3 https://doi.org/10.12688/materialsopenres.17478.1

Introduction

For a sustainable future that circulates materials in perpetuity, 'Design for Recycling' is a vital strategy. However, in the fashion and textile field the approaches offered to achieve this, namely mono-materiality and disassembly, fall short of addressing the complex blended textiles that have already been produced. The fashion industry has committed to using recycled fibres in their products, but these intentions are not easily turned into actions, as many roadblocks exist for both large and small companies (GFA, 2019). Part of the problem is due to a seemingly unresolvable tension between the designers, recyclers and sorters (Elander & Ljungkvist, 2016). Karell and Niinimäki (2019:10) point out "if textile waste material cannot be reliably identified in the sorting phase, it is not possible to direct the material to appropriate recycling processes" and with the wide use of intimately blended yarns and mixed fibre textiles the challenge for sorters is to find ways of organising these complex materials and find onward markets. In manufacture, the blending of textile fibres is common and can improve function, performance (Sinclair, 2014) and in some cases improve a textiles environmental potential, such as longevity (Beton *et al.*, 2014). This paper seeks to addresses the gap in knowledge between sorting (in recovery) and blending activities (in manufacture), expanding current design strategies towards textile recovery.

Building on Karell and Niinimäki's suggestion that the sortability of a product must come first (2019:10), this paper explores a 'Design for Sorting' approach developed from a practice research PhD investigation (Hall, 2021). Specifically, it investigates the complexity of wool/acrylic blends in the mechanical wool recycling industry and is conducted through field research, interviews, and practice research designing recycled fibres into yarns. This paper is divided into three parts: first, an overview of previous research by Author1 is provided (Hall, 2021), from which this research builds. This establishes the complex sorting categories between wool and acrylic in the recycling sector. Secondly, investigated through field research using a conversation with the owner of a now closed recycling facility about their material archive, the research establishes how recycled blending has been conducted historically in the wool recycled industry. Thirdly, supported by interviews with a sorter and recycler, the knowledge created about sorting categories (part one) and recycled blending methods (part two) is applied through the design of four recycled yarns. The findings from the practice research demonstrate three themes, common to both sorting in recovery and blending in manufacture: fibre quality, fibre type and fibre colour. The paper concludes that understanding the relationship between recovery and remanufacture is key to a Design for Sorting approach and should be used alongside existing design for recycling strategies (mono-materiality and disassembly) to expand the recovery potential of a broader range of textile fibres.

Methods

This research uses a bricolage of methods (Vuletich, 2014) which is described as a "critical, multi-perspectival, multi-theoretical and multi-methodological approach to inquiry" (Rogers, 2012:1). It describes how, unlike the engineer, the designer can make do with the tools that are 'at hand' to acquire knowledge (Lévi-Strauss, 1962). This active approach is often adopted by practice research in design allowing the researcher to construct "methods with tools at hand rather than accepting and using pre-existing methodologies" (Yee & Bremner, 2011:4).

The research is split into three parts, exploring sorting, blending, and applying this knowledge in practice. First, an overview of the Author1's previous research (Hall, 2021) outlining the grades and thresholds of wool/acrylic textiles is presented. This is provided for context for which the research in this paper to build upon. Secondly, field research was conducted on 16th August 2018 to the now closed recycling business Henry Day and Sons Ltd, in West Yorkshire. This company was selected as it was the last known wool recycling company that produced recycled yarns and cloth in the UK and aimed to establish how recycled blending occurred historically. This involved a conversation with Charles Day (who provided permission to be named in this research), descendent and owner of Henry Day & Sons within the offices and buildings that had previously been used for the company. The research was framed as an informal conversation, with no planned questions (as in an interview), to create more realistic or naturalistic data with less performativity (Swain & King, 2022). The visit and subsequent conversation centred around the types of waste materials used by the company and how these were transformed into new products. The conversation was directed by a 'show and tell' of the recycled fibre blends from the remaining archives which were located on site. During the conversation, samples of the historical recycled fibres were picked out by Charles to explain the different methods of recycling and describe the products the company had produced. These fibre samples were gifted to the researcher and permission was given by Charles for the conversation to be recorded (but permission was not granted for the recording to be shared or transcribed) to enable an after action review (Morrison & Meliza, 1999) where the samples and audio were revisited, reflected upon and the types of recycled blending were able to be categorised and understood. The recordings have since been deleted.

Thirdly, the findings of the previous two parts were brought together and tested in collaboration with an industrial spinning mill. Working with a commission spinner in Yorkshire, UK, four yarns were designed by Author1 using recycled acrylic fibres sourced from the wool recycling industry in Prato, Italy and other fibres sourced from the spinning facility themselves, such as wool and polyester. The yarns were designed using the same recycled blending techniques established in the field visit/conversation (part 2) and designed so that, after use as a textile, they could flow back into the sorting grades the industry uses for recycling (part 1). This practice research was supported by semi-structured interviews with a recycler (Recycler X, from Prato, Italy who works in the current mechanical wool recycling) in March 2020 and sorter (Hasnain

Lilani who works at 'Recycle Wool' in Pakistan specialising in sorting post-consumer wool jumpers, who gave their permission to be named in the manuscript) in both November 2020 and March 2021. The two interviewees were selected for their first-hand experience in the industry and to provide specific perspectives from recycling and sorting which were relevant to the research. The interviewees were found during prior field research. Recycler X was selected during field research in Prato, Italy because of his work with low value acrylic and wool waste materials. Hasnain Lilani was selected because the research required a perspective from an expert sorter of wool textiles. Through a recommendation from a recycler in Prato, Author1 was put in touch with Lilani who was working directly with sorting waste wool jumpers.

The interviews themselves were planned with general topics of inquiry that Author1 wanted to be addressed. This left space for specific questions to be formed based on the answers the interviewees provided that could be adapted in the moment. The interviews were conducted over WhatsApp, a quick messaging platform for written, spoken and visual communications. This was the medium of choice for both interviewees and enabled fast communication that could be made at any time during the day. This was particularly relevant as both subjects were based over-seas and had busy work lives. The interviews were formed of a mixture of short written communications, longer voice messages and photographs, which are available in *Underlying data* (Hall, 2022). In particular, voice messages proved to be a particularly useful tool when answers could not be simply explained in written form. They also overcame any language barriers as concepts could be explained in less formal language. Visuals were also helpful as it enabled the researcher to explain her questions more clearly. In this way, the interviews became more akin to a conversation (as used in part 2) conducted face-to-face in an industrial context, where it is easy to discuss complex topics, pointing to and picking up physical objects as a form of reference. Transcripts of interviews were sent to the interviewees to review before publication.

Finally, autoethnographic methods (Ellis *et al.,* 2011) were applied to analyse the findings. The practice research was written up and described using an after action review method (Morrison & Meliza, 1999) exploring the basic steps of what had happened during the design and production of the rceycled yarn. A reflection of the text was made using an annotated portfolio method (Gaver & Bowers, 2012; Hall, 2020) in which themes were highlighted and annotations were made to make sense of the experience leading to the findings. Finally, visual thinking methods (Arnheim, 1969; Tufte, 1990) were applied using models/diagrams, the fianl versions of which are presented in this paper. However, the illative process of developing the model was also part of the reflective process used to make sense of the practice research. Ultimately, this bricolage of methods enabled Author1 to produce the final model depicting the relationship between sorting in recovery and blending in manufacture towards a Design for Sorting approach.

Ethics statement

This research was approved by UAL's University Research Degrees Subcommittee (URDSC) on 28th March 2018 and was deemed as minimal ethical risk due to the nature of the research and the study methods employed. Applications deemed minimal ethical risk do not need to be approved by Research and Knowledge Exchange Ethics Sub-Committee (RKEESC).

Written informed consent for publication of the participants details and data (including transcripts in the cases of the semi-structured interviews) was obtained from the participants.

Sorting practices in the wool recycling industry

Sorting goods into categories is the main method used in resource recovery to create value (Gregson *et al.*, 2016). Crang *et al.* (2013:11) point out that the value of used goods is realised through the assessment of material quality, specifically "finding and separating the good quality components or materials". When recycling for the mechanical recovery of fibres there are generally four types that determine a sorting grade: pre-/post-consumer, structure, colour and fibre-type (see Figure 1).

Sorting: Pre-/post-consumer

There are two forms of waste textile, pre- and post-consumer. Pre-consumer is material diverted from waste in the manufacturing process (ISO, 2016) and is the easiest waste-stream to sort because it is most often formed during the manufacturing process (Fontell & Heikkilä, 2017). These wastes, created before they reach the consumer, involve a limited amount of sorting (Heikkila *et al*., 2018), but still require processing before they can be used in remanufacture or recycling streams (Runnel *et al*., 2017; Syrett *et al*., 2021). Post-consumer wastes are discarded by the consumer at the end of use/life, and largely collected in a separate system although, some pre-consumer textiles are directed to post-consumer collection streams, such as unsold garments. Garments, that cannot be re-used in the local market, are recycled at best and incinerated at worst (Wijnia, 2016).

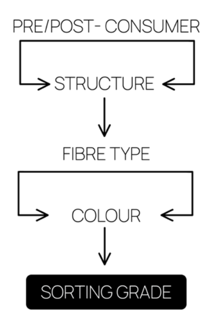

Figure 1. Four types of sorting leading to a sorting grade.

Post-consumer, unlike the pre-consumer waste, cannot be easily collected in homogeneous groups because the textiles are collected from many different users (Roos *et al.*, 2019) and thus, require significant levels of sorting. When collected, it is first sorted into two broad categories: unwearable for recycling and wearable for re-use (Dutch Clothing Mountain, 2017). However, the lines between re-use and recycling are blurred, and re-usable waste streams with no market can leak into recycling grades (Norris, 2012a).

Sorting: Structure

Structure describes the construction method of a textile, such as knit or woven and can significantly impact the recovery of the fibres (Roos *et al.*, 2019). Sorting for structure often occurs accidentally during sorting for re-use where garments are split by type, which tend to divide readily into structures, such as knitted jumpers or woven trousers. Norris (2012a) explains how acrylic knitwear, unlike the 'recycling grade' clothing that is stained, damaged and unwearable, is unmarketable for western re-use and unsuitable for the warm climates of the global second-hand re-use markets. These often become an accidental recycling grade that are already sorted by structure.

Day (2016) explains, that historically the textile recycling industry split waste between shoddy (typically knitted) and Mungo (typically woven) structures in order to obtain longer or shorter fibres in the physical recycling process. Knitted textiles, according to Norris (2012b), are soft and easy to open in the pulling/shredding process whereas, woven materials created using a tighter construction and often requiring stronger more tightly spun yarn, result in shorter recovered fibres (Nørup *et al.*, 2018). If recovered fibres are too short it is difficult to process them to go through the machinery when manufacturing into new textiles. In today's wool recycling industry in Prato, Italy some sorters even go as far as sorting between 'fine' and 'ordinary' knit structures in an attempt to increase the quality of the recycled fibre (Hall, 2018).

Sorting for structure has been highlighted by Near Infra Red (NIR) sorting technology project, Fibersort. Among its recommendations, it proposes that:

> "sorting on woven qualities for instance or separating bales of lower and higher qualities of woolen (sic) textiles, could enable them to be used for different product applications, and hence avoid waste being created later in the value chain" (Fibersort, 2020:15)

However, the importance of this category is contended. Niinimäki and Karell (2020) point out that although a greater understanding of the effects of the structure of our textiles for recycling is required, this is only relevant to chemical recycling and not mechanical recycling. Whilst it is true that the structure of textiles matters little when mechanically recycling low grade textiles into non-woven applications, for higher grade mechanical recycling the industry distinguishes between the structures to obtain quality fibres (Hall, 2018).

Sorting: Colour

Another method to create value from waste textiles is by colour (Uchimaru *et al.*, 2013) and some colours are more desirable than others. According to Norris (2012b:43), "bright shades are at a premium, with sludgy grey mixes at the bottom of the scale". In the Indian shoddy industry, Norris explains, colour sorting is first separated into families and then into shades and sub-shades. Each one can be further qualified as bright, light and dark, referring to depth of colour, shininess and purity of shade. 'Uni' (i.e. solid colour) clothes are the most expensive, 'fancy' (i.e. checks and stripes) are the cheapest. However, you can also make several types of fancy, Norris (2012b) explains, such as red fancy, violet fancy, blue fancy or '10 fancy' (fancy with ten colours in it).

One of the biggest barriers to effective textile recycling is colour contamination and results through inefficient sorting. Contamination presents itself as either sludgy colours or in the form of 'neps'; contrasting coloured specs which stand out and, in some cases, protrude from the yarn or fabric surface. While neps can be exploited as a design feature, it is not practical if a solid colour is required (Hall, 2018).

Sorting: Fibre type

It is generally recognised that high-value textile recycling is centred around mono-material input (Hall, 2018). For example, Prato, Italy has become a hub utilising mono-material wool fibres. Wool, as Botticello (2012) explains, is valued for its fire-retardant qualities for non-woven markets and therefore in the sorting process garments must contain high percentages of wool to be used for this purpose. She points out that in the past jumpers could be sorted into two basic categories, pure wool or synthetic. However, in today's industry wool is "mixed in diverse blends, reducing pure wool content and making the fibre content of the garments more difficult to recognise and categorise" (Botticello, 2012:173).

Acrylic has increasingly been used as a blending agent with wool to maintain the wool-like character in yarns (European Commission, 2003). This combination of 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's wool recycling industry (Hall, 2018).

However, though there have been numerous combinations of wool and acrylic fibres, the wool-based sorting industry has found ways to categorise these complex waste streams for a variety of markets, investigated in the Author1's PhD thesis where the grades and thresholds of wool/acrylic knitted textiles have been outlined (Hall, 2021). As the industry prioritises wool content, the generic sorting grades are described by the percentages of wool they contain, namely 100% wool, 80% wool, 50% wool and 100% acrylic. Due to the complexities of the blends present, these grades depict the average amount of wool a batch/bail will contain and denote the thresholds around each grade (see Figure 2).

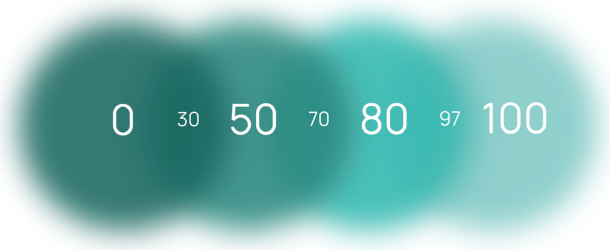

Figure 2. Wool/acrylic sorting grades and thresholds visualised to represent the blurred boundaries between the sorting categories (Hall, 2021).

Author1 found in her PhD research (Hall, 2021) that the average wool content of a bail was often lower than its named composition, such as a bail named 50% wool might only contain 40% wool in practice. This also applies to the 100% acrylic grade, which could contain as much as 15% wool or possibly more. This explains the complexity of the waste in the sorting system and demonstrates the wide overlap that occurs between grades and the 'blurred' boundaries between each sorting category (Figure 2). The research concluded that it is both the generic grades (100% wool, 80% wool, 50% wool and 100% acrylic/0% wool), and the thresholds that begin to provide the designer with the start of a Design for Sorting approach.

Blending practices in the textile industry

Blending is defined by Sinclair (2014:162) as "the bringing together of fibres of different types" and Hatch (1993) explains this practice can be traced back as early as 150 B.C. when cotton and flax yarns were woven together to form a blended material and was used from the 16th until 19th Centuries as a method to reduce costs. Blended yarns were not introduced until 1963 and since then, designers and manufacturers have found further creative ways to combine materials.

More recently, with the rise of cradle-to-cradle principles, blending has been demonised as 'monstrous hybrids' used to create 'Frankenstein products' (Braungart & McDonough, 2002). This refers specifically to the blending of technical and biological materials that cannot be salvaged at the end-of-use (Braungart & McDonough, 2002), however in the context of textiles the combination of natural and synthetic materials is so prevalent it is hard to imagine its removal. It is essential to understand the reasons for fibre blending in order to address the challenge it poses for textile recycling and sorting.

Together Gulich (2006) and Payne (2015) suggest that textiles are designed for a number of reasons such as functionality, appearance and cost and the designer's role is one that attends to these aspects through specification of materials for products, including blending (Gulich, 2006). However, there is often a trade-off to be found between designing functional and durable textiles and designing for recyclability via mono-materiality (Tanttu *et al.*, 2016). Beton *et al*. (2014) point out that in some cases, blending can aid longevity and reduce environmental impacts, for example, incorporating a more durable component might extend the useful life of a fragile fibre. Sinclair (2014) provides five benefits that blending can provide:

- To compensate for weaker attributes or properties of one type of fibre
- To improve the performance of the resulting yarn or fabric
- To improve or provide a different appearance
- To improve the efficiency of processing, especially of spinning, weaving and knitting
- To reduce costs

In recycling practices blending can also be used for similar results, for example, recyclers compensate for the shorter recycled fibres by blending them with longer virgin ones or as a means to control material composition. Norris (2012a) illustrates this by describing the procedures used in the wool recycling industry in India, "in order to increase the wool content of a batch to complete a particular order specifying for example 75 per cent wool, factory managers have to buy in bales of wool-rich rags to mix with existing stocks" (Norris, 2012a:395).

Recycled blending

To further understand the historical practices of recycling wool fibres into high-value yarns and fabrics a field visit to the archive of shoddy recycling business Henry Day and Sons Ltd was conducted. Owner, Charles Day explained why and how sorting and blending methods were used and that all decisions were made according to the requirements of the final product. Although many of these applications do not exist today, it was the design and development of the different combinations of wastes and colours that was most revealing. For example, the company used a combination of different types of textile waste to produce a woollen cloth for Royal Ulster Constabulary overcoats (the police force in Northern Ireland from 1922–2001). This was made with a mixture of recycled woollen and worsted spun woven textiles that, when recycled, produced very short fibres. These were then combined by the yarn spinner with longer virgin wool to create the new yarn. The virgin wool would be dyed so that when blended with the recycled fibre it would form the exact Royal Ulster Constabulary shade. This demonstrated recycled and virgin combinations as well as colour blending as an approach.

In another example, a recycled fibre was labelled 'NBC (National Bus Company), double carded 1975'. The fibre composition was 55% Shoddy (knitted wool waste, longer fibres), 25% Dyed Wool (virgin) and 10% Brush (woven worsted waste, shorter fibres). The remaining 10% 'Harwood' fibre was pre-consumer waste sourced from a local company by the same name that produced yarn and woven fabric. Although Charles was unable to confirm the specific type of pre-consumer waste (from one of many stages during yarn or woven production), the sample illustrated how recycled and virgin; pre- and post-consumer; knitted and woven; and long and short fibres had been specifically designed to create the final blend for the product. From the discussion four additional categories of blending emerged, over and above blending different fibre types together: recycled & virgin, pre & post-consumer, colour and structure.

Recycled blending: Recycled and virgin. Longer virgin fibres outperform the shorter recycled ones that have been ripped from the cloth in the recycling process (Merati & Okamura, 2004) and the addition of virgin fibre is often required to aid the movement of the recycled fibres as they travel through yarn spinning machinery. Sakthivel *et al.* (2010) estimate that this addition of virgin content is about 15% in the shoddy industry, and is also used, as it is in standard production, for functionality, appearance and cost benefits. For example, recycled fibre of any type is often blended with synthetics (mixing both virgin and recycled with different fibre types) chosen for their strength and economic price point.

Rather than virgin fibres supporting the recycled content, the reverse is also possible with smaller amounts of recycled fibres blended with virgin to save on costs. For example, seam waste from the cleaning process of cashmere jumpers could be added to a virgin batch to achieve a 10 or 20% cashmere blend (Hall, 2018). Hence the addition of recycled materials can be used to promote the luxury qualities of cashmere at a low price point.

Recycled blending: pre- and post-consumer. The blending of different types of waste, pre- and post-consumer, is used in the recycling industry to control the quality of the textile materials produced (Hall, 2018). As previously discussed, pre-consumer wastes covers a range of materials, but is generally sourced in more consistent fibre type, colour and structure than their post-consumer counterparts (Fontell & Heikkilä, 2017) and therefore might be described as 'high quality'. While the details of a pre-consumer system can be complex (Runnel *et al.*, 2017), this approach is made easier when a recycling industry is located within an area of virgin production. For example, the wool recycling industry in Italy is located within Prato which also has virgin wool textile production. While the recyclers in Prato import post-consumer waste, they also have easy access to the local industry waste (Roos *et al.*, 2019). However, this is often more expensive then utilising post-consumer (Hall, 2018). As with all other blending, it ultimately occurs in order to balance the requirements of the final material.

Recycled blending: Colour. As previously discussed, sorting waste by colour is one of the most common methods used in the industry. This eliminates the need to strip the colour from the material. Any recycled fibre colour can be used as-is or blended with others to create a specific shade, yet, as Norris (2005) points out, in the shoddy industry, colour choice is often determined by availability. If a colour is fashionable one year the industry may struggle to provide the fibres needed to create the exact colour blend. Conversely, when that trend comes to an end, recyclers may end up with too much of a given colour.

If the shade cannot be obtained by the available recycled fibres, an overdyeing method can be used for a whole batch or a part-batch in a blend (Hall, 2018). For example, a light green fibre could be overdyed to create a darker green shade, this, in turn, might be used with a variety of other colours to form an exact shade. However, overdyeing recycled fibres, particularly those which are impure, can be problematic and often rather than using overdyed recycled fibres, more sustainably dyed virgin fibres can be added to fulfil the requirements of the colour blend (ECAP, 2019). This combined approach (blending colour and virgin fibre) is commonplace within the recycling industry and has been developed for use with complex sources of waste material.

Recycled blending: Structure. Historically the wool recycling industry grouped materials according to their structure, named Shoddy and Mungo (Day, 2016) and this approach is still used in today's mechanical recycling industry (Hall, 2018). While the main focus of sorting technology research has concentrated on fibre type, the importance of sorting by structure has started to be realised (Fibersort, 2020). The different fibre lengths produced from the two textile structures can be combined for the advantage of the spinner. For example, blending shorter, lower quality, cheaper fibres with the longer, more expensive ones can help control the quality and economic value of the final material. Alternatively, shorter fibre can be included to benefit the performance of a later production stage. For example, the milling process used on wool fabrics to achieve a controlled felted finish, as Pailthorpe and Wood (2012) explain, is made easier when shorter wool fibres are present in the yarns.

Field testing: Sorting and blending

Having established the sorting methods, in particular the grades and thresholds of knitted waste in the wool recycling industry, and the recycled blending methods for designing high-value yarns, a design test was devised to explore the relationship between these two practices in the mechanical recycling industry. 100% recycled acrylic fibres were sourced directly from the wool recycling industry, Prato, Italy which would usually be used for non-woven shoddy materials or as yarns for blankets sold in markets outside of Europe. Although described as 100% acrylic, as the previous the research demonstrates (Hall, 2021), this could in fact contain a variety of fibres including wool. Instead of this typical route, a new product pathway (an additional loop) was designed to return the acrylic into a knitwear product for the European marketplace (Figure 3). This fibre grade (100% acrylic) was selected as a worst-case scenario to demonstrate how this lowest value grade could be designed using recycled blending and at the same time into new sorting categories for its onward recyclability. After this additional loop, which provides fibre longevity, the fibres could then continue with their typical recycling routes or by design be diverted into other loops and streams.

In collaboration with a commission yarn spinning facility (who wish to remain anonymous) in Yorkshire, UK, using a woollen system to produce ring-spun yarns, four yarns were designed for different market levels from basic to luxury and briefs created accordingly. All four yarns were required to be suitable for a knitted garment that could be sold in the European market which was achieved through the expert knowledge provided by the yarn spinner for industrial yarn creation and the tacit design knowledge brought by Author1 (designer-researcher) who previously worked at a knitwear designer for the UK high-street. In addition, there were technical requirements the spinner required. For example, he would not accept more than 50% recycled acrylic in the blend to ensure it could be processed by the machinery. Finally, the designer-researcher also required each yarn to fall into a specific recycling grade, therefore the final yarns needed to contain either: 0% wool to return to the same category; 30% wool the threshold for the 50% category so it could move up a grade; or 50% wool guaranteeing it would move up a grade. The four yarns were designed and developed, using the recycled acrylic sourced from the recycling industry in Prato, Italy and combined with fibres sourced from stock at the spinning facility (wool/cashmere/mohair) or specially sourced by the spinner from the industry for the blend (recycled polyester from plastic bottles). The design of the yarns have been described in Table 1 and are discussed according to the

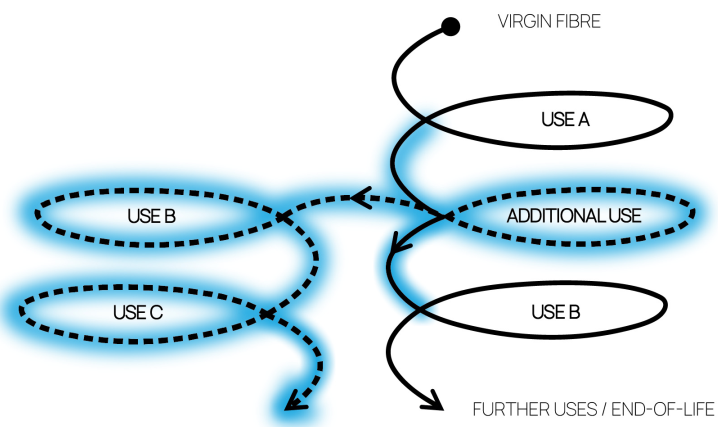

Figure 3. Designing an additional loop which continues into the same pathway or is diverted into another pathway.

Table 1. Four recycled yarns designed using recycling blending techniques for specific wool sorting categories.

YARN	%	FIBRE TYPE	WASTE TYPE	RECYCLED/ VIRGIN	COLOUR
1 Simple	**50%**	**Acrylic**	**Post-Consumer**	**Recycled**	**Navy**
	50%	Polyester	Post-Consumer	Recycled	Black
2 Every day	**50%**	**Acrylic**	**Post-Consumer**	**Recycled**	**Navy**
	30%	Wool	-	Virgin	Black / Turq /Green
	20%	Polyester	Post-Consumer	Recycled	Black
3 Luxury	**50%**	**Acrylic**	**Post-Consumer**	**Recycled**	**Navy**
	20%	Wool	-	Virgin	Slate Blue
	10%	Cashmere	Pre-Consumer	Recovered*	Brown
	20%	Polyester	Post-Consumer	Recycled	Black
4 Super Luxury	**50%**	**Acrylic**	**Post-Consumer**	**Recycled**	**Navy**
	50%	Mohair/Wool/ Cashmere	-	Virgin	White/Lemon/ Honey Bird /Black

* Recovered fibres is a "material that would have otherwise been disposed of as waste… instead been collected and recovered [reclaimed] as a material Input, in lieu of new primary material, for a recycling or a manufacturing process" (ISO, 2016:15)

recycled blending techniques below. Figure 4 also shows four recycled yarns designed for the basic to luxury markets.

Designing: Structure

Out of the all the methods of recycled blending, using waste produced from different structures was explored least in this practice. The recycled acrylic content, for all the yarns, was sourced from knitted waste only. The traditional route when recycling textiles takes knit or woven materials and recycles them into woven or non-woven materials. As sorter Hasain Lilani explains "[recyclers] prefer the knits. They are using knit material and turning it into woven" (Hall, 2021:280). While knitted products produce longer fibres in recovery, the opposite is true of more tightly woven materials. Therefore, intervention by design of these pathways is vital. While it was not possible to combine woven and knitted wastes, due to limited time and difficulty sourcing, the practice did demonstrate how the wastes from knitted textiles could be designed back into a knitted application.

Moreover, three of the yarns also contained recycled polyester (recycled PET - polyethylene terephthalate) and this was sourced from plastic bottles outside the textile industry combining waste from a completely different structure category. The recycled PET was chosen specifically due to its strength (function) and economic price point (cost) which are reasons that blends such as these occur in the virgin spinning industry (Sinclair, 2014). PET from plastic bottles can be recycled mechanically (polymer level) to a good standard or chemically (monomer level) to near virgin quality (Harmsen *et al.,* 2021). While, the recycling of PET plastic bottles face similar challenges to textiles in that it requires rigorous sorting and disassembly (cleaning) to avoid contaminants (Ragaert *et al.,* 2017), regularly the textile industry uses PET from plastic bottles and not from PET textiles. This is put down to the added complexity of our textiles, with many components, compared to the relatively simple design of plastic products (Payne, 2015), that makes plastics bottles an easier waste stream to capture and convert. However, if we continue to use PET from plastic bottles which will enter the textile recycling systems that are not recovered, then we cannot fully transition to a circular economy. The use of PET from plastic bottles does, however, demonstrate how different structures, in this case knitted textiles producing short fibres and PET bottles producing stronger fibres can be utilised to support each other. Using this method Yarn 1 also was the only yarn that could be classified at 100% recycled.

Figure 4. Four recycled yarns designed basic to luxury markets.

Designing: Colour

Less has been investigated in the literature about the nuances of colour sorting for the design of yarns in the wool industry beyond sorting into family colours and specific shades. Therefore, the yarns were designed not to stray too far from the colour of the main recycled acrylic fibre. Across the four yarns produced different amounts of colour blending were employed. Yarn 1, for example, used the least amount of colour blending, combining navy and black to create a deeper shade of navy and Yarn 3 used a very subtle colour combination: Navy (50% acrylic), Slate Blue (20% wool), Brown (10% cashmere) and Black (20% polyester). This resulted in deep and rich navy that although contained slate blue and brown hues was designed to still look like a solid colour (see Figure 5).

On the other hand, Yarn 2 started to combine bolder colours: Navy (50% Acrylic), Black (10% wool), Turquoise (10% wool) and Green (10% wool). This resulted in a melange turquoise-navy. Finally, Yarn 4 blended the most contrasting colours: Navy (50% acrylic), White (17% Mohair), Lemon yellow (12% wool, mohair, cashmere) and Honeybird Blue (12% wool, mohair, cashmere). This produced a turquoise/green melange looking yarn with flashes of lemon and blue (see Figure 6).

To further understand the consequences for the different approaches to designing colour into the yarns, a semi-structured interview with sorter Hasnain Lilani was conducted. Lilani explains sorting solid colours is the most desirable, however, melange garments can also be sorted into 'double tone' grades. He warns, however, that there is not always enough quantity to create a full batch. Solid colours, therefore, hold the highest value acting as a reminder that value is not only attached to the fibre type of the garments. In addition, another semi-structured interview with Recycler X was conducted to provide a recyclers perspective on the subject. Recycler X explained non-solid coloured waste textiles have to be dealt with differently. He confirmed that recyclers do make their own blended recipes from the solid colours, but that melange and fancy waste streams have more limited pathways. Jumpers with melange colours can only be used to re-create new melange shades. Therefore, whilst melange may hold some value, they are not as useful as solid colours which can be used to produce both solid and melange yarns.

Fancy fabrics, those with many colours and patterns, Recycler X illuminates, can be recycled into yarns through overdyeing them with darker colours. The ability to overdye the fibre is dependent on the fibre composition being compatible, such as wool/acrylic, wool/nylon, wool/polyester or better still a pure wool or pure acrylic. However, if the composition cannot be assessed then overdying is not practical and the recycled fibre

Figure 5. **Yarn 1 (left) and Yarn 3 (right) as knitted swatches.**

Figure 6. **Yarn 2 (left) and Yarn 4 (right) as knitted swatches.**

can only be used in hidden applications such as insulation felts.

In fancy patterned fabrics and those produced from fancy yarns with contrasting colours, the sorting strategies also become more complex. In some cases, they can be used to create yarns with coloured neps (referred to by Recycler X as a 'button'), however, only for the simplest 'fancy' categories with two colours. When a textile contains multiple colours or neps, Recycler X explains, it is difficult to know which colour category it should be used within. Therefore, it cannot be recycled back into a new yarn and would only be used in other textile forms where colour is less of a priority.

Designing: Waste type (pre- and post-consumer)

The majority of the yarns in this research were designed with post-consumer wastes, including the polyester fibres sourced from used plastic bottles. There was only one example, Yarn 3, which also contained pre-consumer waste cashmere from the spinning facility. This fibre was left over from a previous production, and therefore should not be classified at recycled, as it "capable of being reclaimed within the same process that generated it." (ISO, 2016:15) but can be defined at recovered, described by ISO (2016:15) as a "material that would have otherwise been disposed of as waste… instead been collected and recovered [reclaimed] as a material Input, in lieu of new primary material, for a recycling or a manufacturing process".

This method, combining different waste sources is cost-effective, as only a small production run of yarn was produced (50kg of each yarn matching the spinning companies minimum order quantities) hence suitable for capitalising on only small quantities of available recovered luxury fibre. Therefore, by adding cashmere, a softer quality yarn/textile was produced and would likely fetch a higher market value. Finally, this method of blending also increased the recycled/recovered content of the yarn, and therefore, had demonstratable sustainability credentials.

Designing: Recycled and virgin

All the yarns produced contained 50% recycled acrylic, but the virgin content varied in percentage. For example, Yarn 4 was designed with a 50% virgin blend of wool/mohair/cashmere, whereas Yarn 2 and 3 all contained 30% virgin wool. Virgin content (or other types of longer fibres) is necessary to aid the manufacture process including the speed at which the fibres can be processed, the yield (amount of yarn produced minus the wastage) and the thickness/count of the yarn. Iterations between the designer-researcher and the spinning engineer ensured that the design for market and for sortability balanced with the requirements of manufacture. For example, the spinning engineer would not accept any higher than 50% recycled acrylic, as the fibres were too short whilst the other recycled content, polyester and cashmere, had longer fibres length as they were sourced from non-post-consumer wastes.

The use of virgin wool was used to ensure the yarns and later textiles would enter into improved sorting grades at the end of their useful lives. Even though 100% recycled acrylic was sourced for this research, the same blending principle could also be applied to other waste grades, such as 50% wool/50% acrylic and thereby would increase the wool content even further. The variety of virgin fibres were selected based on different market levels (described as simple, every day, luxury and super luxury), and thus exploring how easy or difficult it would be to create yarns for knitwear across these market levels using recycled content. This was the reason polyester, a cheaper fibre than wool, was selected to be part of yarn 1, 2 and 3's blend.

At first virgin acrylic fibre was considered, to enable mono-materiality in Yarn 1, however due to minimum quantity order limitations it could not be sourced and happily avoided further demand for virgin acrylic fibres- problematic due to the chemical nature of this man-made fibre (Fletcher, 2008). Nylon also could not be used because the woollen spinning system to produce ring-spun yarn could only cope with 20% nylon or below and so was discounted because Yarn 1 required 50% non-wool virgin content to re-enter the same 100% acrylic sorting grade. Thus recycled polyester was selected which is widely available.

However, this choice of synthetic fibres would also have an impact at the sorting stage and would be considered a contaminant in exactly the same way as the recycled acrylic because value, at the sorting stage, is only attributed to the percentage of wool. Therefore, in the case of Yarn 2 (Acrylic, Wool and Polyester) the polyester would be grouped together with the acrylic and described as acrylic/synthetic. This, does not however, provide the green light for designers to create blends from synthetic virgin materials without any consideration for the consequences and is only appropriate when designing with complex recycled fibres directly for a known sorting and recycling systems.

Discussion – design for sorting

This research has explored the historical and present-day methods used by the wool recycling industry to recover and manufacture recycled fibres for a range of end-markets. It provided four methods of sorting used to categorise waste textiles (see Figure 7). In addition, recycled blending techniques have adapted creatively to overcome the challenges of using recycled fibres across five categories (see Figure 7), some of which overlap with methods used in the virgin textile industry. These blending techniques are dictated by the end application/market which has been illustrated in this research through the design of four yarns: simple, every day, luxury and super luxury. However, it is the relationship between the methods of sorting in recovery and blending in manufacture that is most enlightening and has resulted in three themes: fibre quality, fibre type and fibre colour (see Figure 7). Each of these categories has been expanded below and have been supported by expert interviews.

Design for Sorting: Fibre quality

Fibre quality is one of the biggest challenges for the manufacture of recycled materials. Quality, here, refers to fibre length obtained after shredding but could have an expanded definition to include attributes of these fibres when manufactured such as yarn spinning. For example, the yarn tenacity, thick or thin areas, neps and hairiness etc (Vadicherla & Saravanan, 2017). In the recovery phase, sorting waste textiles for fibre quality is assessed via three sorting methods: pre/post-consumer textiles, structure, and virgin and recycled.

The different fibre lengths obtainable from virgin and recycled fibres are well known, however it is the other two categories that will be focused on here. As previously discussed, waste textiles are sourced from pre-consumer and post-consumer streams. Pre-consumer usually create higher quality fibres during recycling because they have either been processed less or they have no degradation due to wear. For example, spinning waste is easier to shred as it has not been knitted or woven into a textile. In addition, material production offcuts can be easier to obtain fibres from, unlike for example, an old, felted wool jumper accidentally washed at too high a temperature. This is a simplified view of the pre-consumer recycling system which is much more complex (Runnel *et al.*, 2017). However, if collected straight from the factory, pre-consumer waste, has the potential to have increased fibre quality (Fontell & Heikkilä, 2017). In addition, relevant to the next two categories, pre-consumer waste also requires minimal sorting to ensure fibre type and colour are maintained, as the waste is collected from the production of large quantities of the same manufactured products (Fontell & Heikkilä, 2017). Post-consumer textile waste, on the other hand, is sorted for quality via structure which also dictates fibre length.

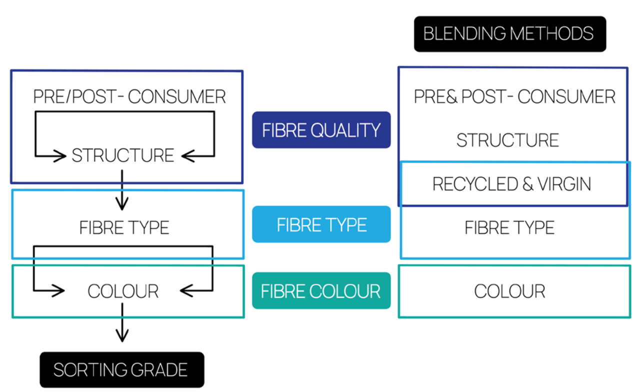

Figure 7. Design for Sorting as three themes bridging sorting methods in recovery with blending methods in manufacture.

In manufacture, at yarn level the designer can blend different fibres (short and long) to create a product. This can also be used as a way to ensure longevity of all resources not just the longest quality fibres. For future recycling, it also illustrates that the choices made by the designer regarding the construction of the textile across yarn, material and product level also impact recovery. For example, the value of fibre quality will be affected by how tight the yarn is spun (yarn level), how tightly the knit of weave is produced (material level) and finally how different structured materials are combined, such as a coat with a loosely woven outer shell and a tightly woven inner lining (product level). This final product level consideration is relevant as to ensure fibre quality in recycling each fabric construction would need to be separated to enable machinery to pull long fibres from the outer in a separate process to the shorter fibres of the lining. Each of these levels represent design decisions that will impact the recycled value of the resource in its next life.

For the designer, this knowledge of quality and how it materialises itself is the key to design intervention and provides designers with ways to create new pathways from more tricky waste types and without adding unnecessary attributes into the textile. In this research, proof of concept was offered using recycled fibres from knitted structures (high value) and diverting them away from woven high spun yarns into looser yarns for knitwear that can easily be recycled again. Naturally, In the next life the fibres may be too short to use for knitted products and therefore could be designed into a tightly spun yarn (keeping the fibre securely in place) for woven textiles. The designer, therefore, can intervene and create new ways of using these fibres to maximise their use. Ultimately, as Norris (2012c:140) expresses, if we are to create value from waste textiles we need "to keep it moving, keep sorting and recombining it, imagining new contexts and creating those pathways".

Design for sorting: Fibre type

Addressing this challenge of low value mixed fibres through design was the focus of this research specifically where mono materiality via chemical separation is currently not possible. In the mechanical recycling industry, the previous research (Hall, 2021) provided generic grades and thresholds that describe the complex blends. It has been established that value is determined at the sorting stage where the highest value is assigned to the purest recycled wool fibres (mainly but not completely pure wool) and lowest value to most synthetic content (mainly but not completely pure synthetic).

The use of lower value fibre types was expanded in the interview by sorter Hasnain Lilani. Although his business model is primarily focused on sorting wool products, describing acrylic as 'completely wasted', he explains that lower value synthetics are used by his clients (recyclers) to reduce the price of the materials they are producing. This method of sourcing different fibre types to blend afterwards in manufacture enables the industry to organise and utilise wastes effectively, as well as regain control of the fibre content to create new textile material.

In addition to blending different recycled wastes from the sorting system, it is also possible to blend different recycled and virgin fibre types to control the content. Although this might seem like an obvious solution, in this research this method was used to design yarns that, after use, would return to specific categories in the sorting system. This is especially relevant, as it is easy to utilise the highest value recycled fibres (100% wool grade), whereas this research illustrates that it is also possible to use the lowest value fibres (100% acrylic grade). This is achieved by blending different percentages of wool into the yarns. Yarn 1 was designed to gain at least one additional loop and thereafter return to the same 100% acrylic/synthetic category to then flow into the typical markets such as non-woven materials. Yarn 2 and 3 were designed to sit on the edge of the threshold for the 50% wool category. This, therefore, has the potential to move up a category diverting the material away from its typical route. Finally, Yarn 4 more substantially moves up a category. The aim of this approach was to address how to utilise the most complex wastes that already exist and create a range of solutions to replace virgin production.

Moreover, even though this research took a focused look at blending that occurs at yarn level, blending at material level, such as combining two yarns of different compositions, and product level, such as combining multiple materials with different compositions together, should not be forgotten. Any further blending across the textile hierarchy would also have an impact at the sorting stage thus the designer must take all levels of blending into account (see Hall, 2021).

Design for sorting: Fibre colour

Sorting for colour is a cornerstone of the mechanical recycling industry as the colour is carried forward into its next life. Colour sorting is meticulously conducted as a method to increase value during the recovery phase, such as into family colours, shades etc... There is a mismatch, however, between the efforts made in recovery to keep these colours pure and the combining of colours during the manufacture of yarns. While in this research the colours of the four yarns were kept to a minimum this led to wider conversation with experts Hasnain Lilani and Recycler X about how colour is used in the recycling industry.

Solid colours, such as Yarn 1, hold the highest value. However, as Yarn 3 illustrated it is still possible to combine small quantities of other colours (Navy, Slate blue, Brown and Black) to produce very subtle tones that would be classified as solid in the sorting stage. Marl colours, such as Yarn 2 (Navy, Turquoise, Green, Black) can be sorted into what Liliani describes as 'double tones', but this type of sorting starts to become more complex. In manufacture, Recycler X expands, it is easy to move a solid to a marl and it is also possible, but just not as simple, to create a marl from a marl. However, it becomes trickier when creating complex marls, such as Yarn 4 (Navy, Yellow, Blue and White). Yet, both Liliani and Recycler X were confident that this yarn could also be sorted (when there was demand for this marl colour of waste) and manufactured into a new marl shade.

It should be noted that fancy textiles become much more complex at material and product level and this causes the biggest reduction in value. The more intricate the pattern and more contrasting the colours, the more problematic for sorting and manufacture. However, as Lialni explains:

> "If jumpers are half solid and half fancy, we cut the half out and put this into the solid category and remaining half is kept separately in the fancy category"

Recycler X expands this discussion even further. Fancy textiles can be divided into: subtle and bold categories. More subtle combinations can avoid value degradation, for example Recycler X explains:

> "if it is [a] knitted jumper with dark blue and black you can put it in either the blue or the black sorting category. A little navy in the black is not a problem"

Unfortunately, this does not always apply to woven materials as these are considered by Recycler X as lower value. Bolder, more brightly coloured patterned textiles however, automatically loose value and are best suited for non-woven applications. Alternatively, they can be overdyed with a darker colour, such as black, brown or navy to be used as a solid colour alone or in a blend.

Just as this research has demonstrated with fibre quality and fibre type, design intervention could be used to find methods to valorise all manners of melange and fancy waste. Thus, in the same way as designing to incrementally increase the value of fibre type, the value of fibre colour could be harnessed.

Design for sorting: Combined approach

While it is useful to clearly outline each element: fibre quality, type, and colour, these themes that connect recovery and manufacture cannot be used alone. It is only understanding the impacts of each of these themes together that a Design for Sorting approach can be found.

This point was emphasised by Lilani at the end of his interview talking about sorting fancy, high percentage wool, chunky knitted jumpers:

> "most of the customers want to take these materials because they are less expensive. The quality is really good because most of the fancy sweaters come in heavy sweaters and mostly pure wool and the quality is super super nice. For recycling it is worth nothing, it has low value"

Here, Lilani demonstrates that although these garments can be sorted into pure fibre type and fall into the heavy knit category that would produce long fibre length, the fact that the jumpers are 'fancy' with a mix of colours brings there value down. Yet, it is only the fibre colour that causes this garment to fall in value at the sorting stage and this in turn dictates how it will be used in its next life.

The benefit of understanding each theme is also evident in the manufacture of recycled materials. For example, where a textile has lost value due to colour, this can be compensated by overdying, but only if the fibre type can be established. Furthermore, dyed virgin fibres could be added to the yarn, to effect, not only, the colour but this new fibre will have huge impact on fibre quality of the blend.

Both of these examples highlight that for the Design for Sorting approach to be successful it is not only about combining different fibre qualities, types and colours from the existing waste available to create yarns, it is also understanding how these choices impact recovery at the end of the next use. As a designer you might add recycled value in one area but loose it in the other. It would be easy for this research to conclude that designers should only select the loosest knits with the purest composition and colour (the cream of the recycling industry) and design them back into the same 'cream' textile garments (solid, pure wool knits). However, these types of waste are already desirable sorting categories in the mechanical wool recycling industry and only selecting these fails to address the rest of the waste that is available. Furthermore, this narrow approach of only manufacturing 'the cream' from 'the cream' does not account for the vast range of textiles that are required across the industry. For a circular economy we require a range of wastes to flow into variety of end uses; a balance needs to be struck. This balance offers a challenge to the designer wanting to Design for Sorting where designs are created knowing how the resources can suitably transform in their subsequent lives. It is this level of foresight that the textile design industry has found difficult. Often products are disposed of after their second life (Payne, 2015) and as McDonough & Braungart (2013) explain, this happens when designers become preoccupied with making an object 'work' in its first cycle that we forget to look forward to what happens next.

Therefore, the Design for Sorting approach provides the opportunity to elongate resource life (ideally in addition to product life) of complex wastes by expanding our view of the many resource loops that could exist and enabling us to design extra uses or loops in the lifecycle that they would not have had otherwise. However, it is unrealistic to think that all fibres should be designed into an extra 'yarn loop' rather than move into other products that are considered lower value, such as non-woven materials. Rather this research provides designers with an expanded range of options to design for recovery (through sorting) so that all types and values of textile fibres can be utilised effectively. It is only armed with this knowledge that appropriate additional pathways can be forged, through design, to support a circular economy (see Figure 8).

Finally, further research building on the insights presented here should be undertaken to develop this concept across other fibres and recycling types but particularly addressing the impacts at material and product level towards a fully formed Design for Sorting approach. It should be noted that the findings in the research where supported by two expert semi-structured interviews. The decision to use only two interviews could be considered a small sample size, however, this was deemed appropriate to accomplish the research

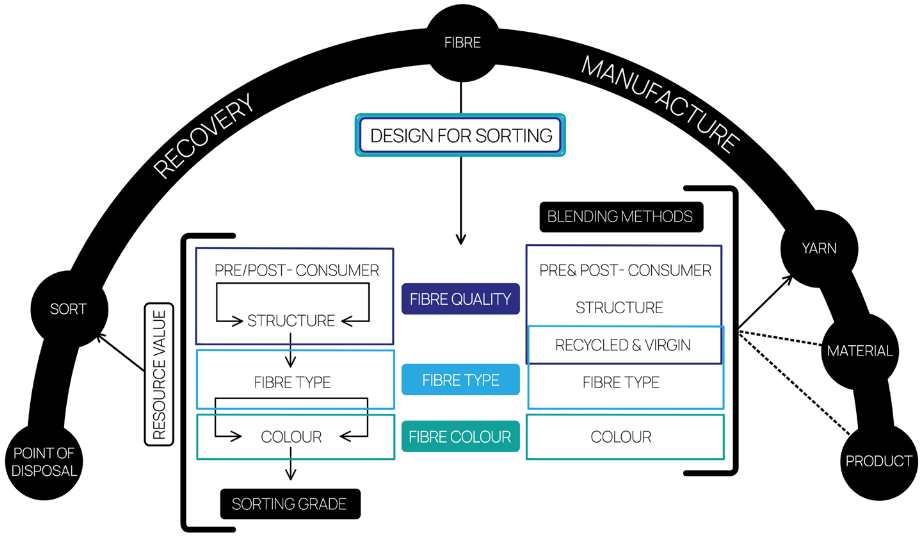

Figure 8. Design for Sorting between recovery and manufacture.

aims of exploring design approaches. It would be recommended that further interviews and data could be produced to expand this field of research.

Conclusions

This research provides three 'Design for Sorting' themes that act as a bridge between the five methods of recycled blending in manufacture and the four methods of sorting within textile recovery. Armed with this knowledge, design can intervene to design from recycled wastes and simultaneously influence the resource pathways for onward recyclability. Each 'Design for Sorting' theme: fibre quality, fibre type and fibre colour needs to be understood, but do not stand alone. Thus, by establishing the impacts of all three themes combined the designer can influence fibre value in recovery.

Ultimately this research arms the designer with a better understanding of the impacts of their design choices in recovery. We need, as Goldsworthy and Politowicz (2019:14) explain, to change "how we view and design products, not as static objects but as dynamic and evolving systems", and in using this approach, designers can start matching the appropriate recycled fibres and blending techniques to create functional and marketable products with an understanding of how they might be recirculated. Ultimately, the designer can use their creativity to extend the life of complex recycled textile fibres and if used alongside existing 'Design for Recycling' strategies (mono-materiality and disassembly) can support the recovery of an expanded range of fibres in our textile system.

Data availability

Underlying data

University of the Arts London research repository (Figshare): DESIGN FOR SORTING KNITWEAR - Interview transcripts with textile sorter and recycler.

https://doi.org/10.25441/arts.20502261.v1 (Hall, 2022).

This project contains the following underlying data:

Data1_Interview_Sorter.pdf (interview transcript with textile sorter).

Data2_Interview_Recycler.pdf (interview transcript with textile recycler).

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

References

Arnheim R: **Visual thinking.** Berkeley ; London: University of California Press. 1969.
Reference Source

Beton A, Cordella M, Dodd N, *et al.*: **Environmental improvement potential of textiles (IMPRO Textiles).** Luxembourg: Publications Office. 2014; (Accessed: 13 November 2018).
Reference Source

Botticello J: **Between Classification, Objectification, and Perception: Processing Secondhand Clothing for Recycling and Reuse.** *TEXTILE.* 2012; **10**(2): 164–183.
Publisher Full Text

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

Crang M, Hughes A, Gregson N, *et al.*: **Rethinking governance and value in commodity chains through global recycling networks.** *Transactions of the Institute of British Geographers.* 2013; **38**(1): 12–24.
Publisher Full Text

Day C: **Waste Textiles Terms and Definitions'.** Henry Day & Sons Ltd. 2016;

(Accessed: 9 May 2019).
Reference Source

Dutch Clothing Mountain: **Measuring the Dutch clothing mountain: Data for sustainability-oriented studies and actions in the apparel sector.** Amsterdam: Hogeschool van Amsterdam. 2017; (Accessed: 13 February 2018).
Reference Source

ECAP: **WE Fashion Case Study. Amsterdam, Netherlands: Rijkswaterstaat: Ministry of Infrastructure and the Enviroment.** 2019; (Accessed: 10 April 2020).
Reference Source

Elander M, Ljungkvist H: **Critical aspects in design for fibre-to-fibre recycling of textiles.** IVL Swedish Environmental Research Institute. 2016; (Accessed: 10 March 2017).
Reference Source

Ellis C, Adams TE, Bochner AP: **Autoethnografie: Ein ÜberblickAutoethnography: An Overview.** *Historical Social Research.* Volumes per year: 1. 2011; **36**(4): 273–290.
Publisher Full Text

European Commission: **Integrated Pollution Prevention and Control (IPPC) - Reference Document on Best Available Techniques for the Textiles Industry.** European Commission. 2003; 626. (Accessed: 17 March 2020).
Reference Source

Fibersort: **Fibersort: Overcoming barriers for long-term implementation.** Amsterdam, The Netherlands: Interreg North-West Europe and Circle Economy. 2020; (Accessed: 18 March 2020).
Reference Source

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

Fontell P, Heikkilä, P: **Model of circular business ecosystem for textiles.** VTT Technology 313. Finland: VTT. 2017; 62. (Accessed: 28 March 2021).
Reference Source

Gaver B, Bowers J: **Annotated portfolios.** *Interactions.* 2012; **19**(4): 40.
Publisher Full Text

GFA: **Pulse of the Fashion Industry Update.** Gobal Fashion Agenda and the Boston Consulting Group, Inc. 2019; (Accessed: 8 October 2019).
Reference Source

Goldsworthy K, Politowicz K: **Fast-Forward: Proposals for a Light and Restorative Fashion Alternative.** In: *Futurescan 4: Valuing Practice, Post-conference proceedings.* Bolton, UK. 2019; (Accessed: 25 June 2021).
Reference Source

Gregson N, Crang M, Botticello J, *et al.*: **Doing the 'dirty work' of the green economy: Resource recovery and migrant labour in the EU.** *Eur Urban Reg Stud.* 2016; 0969776414554489.
Publisher Full Text

Gulich B: **Designing textile products that are easy to recycle.** In: Y. Wang (ed.) *Recycling in textiles*. Cambridge : Boca Raton, Fla: Woodhead ; CRC Press (Woodhead publishing in textiles). 2006.
Reference Source

Hall C: **MIXING IT UP IN PRATO: identifying innovation hotspots within mechanical textile recycling.** In: *Global Fashion Conference.* London: GFC, 2018. 2018; (Accessed: 31 May 2019).
Reference Source

Hall C: **TAKING NOTE: Annotated Portfolio as a Method to Analyse the Experience of Design Research Practice.** *Journal of Textile Design Research and Practice.* 8(2-Futurescan 4: Valuing Practice), 2020; 1–23.
Publisher Full Text

Hall CA: **Design for Recycling Knitwear: a framework for sorting, blending and cascading in the mechanical textile recycling industry.** PhD Thesis. University of the Arts London. 2021.
Reference Source

Hall C: **DESIGN FOR SORTING KNITWEAR - Interview transcripts with textile sorter and recycler.** University of the Arts London. Dataset. 2022.
http://www.doi.org/10.25441/arts.20502261.v1

Harmsen P, Scheffer M, Bos H: **Textiles for Circular Fashion: The Logic behind Recycling Options.** *Sustainability.* 2021; **13**(17): 9714.
Publisher Full Text

Hatch KL: **Textile science.** Minneapolis/Saint Paul: West Publishing Company. 1993.

Heikkilä P, Fontell P, Määttänen M, *et al.*: **Review of Textile Recycling Ecosystem and a Case for Cotton.** In: K. Niinimäki (ed.) *Sustainable Fashion in a Circular Economy.* Aalto, Finland: Springer International Publishing, 2018.
Reference Source

ISO: **Environmental labels and declarations - self-declared environmental claims (type II environmental labelling).** International Organization for Standardization, 2016.
Reference Source

Karell E, Niinimäki K: **Addressing the Dialogue between Design, Sorting and Recycling in a Circular Economy.** *The Design Journal.* 2019; **22**(sup1): 997–1013.
Publisher Full Text

Lévi-Strauss C: **The savage mind.** Chicago, IL: University of Chicago Press, 1962.

McDonough W, Braungart M: **The Upcycle: Beyond Sustainability--Designing for Abundance.** New York: North Point Press, 2013.
Reference Source

Merati AA, Okamura M: **Producing Medium Count Yarns from Recycled Fibers with Friction Spinning.** *Text Res J.* 2004; **74**(7): 640–645.
Publisher Full Text

Morrison JE, Meliza LL: **Foundations of the After Action Review Process.** IDA/HQ-D2332. INSTITUTE FOR DEFENSE ANALYSES ALEXANDRIA VA. 1999; (Accessed: 14 June 2021).
Reference Source

Niinimäki K, Karell E: **Closing the Loop: Intentional Fashion Design Defined by Recycling Technologies.** In: G. Vignali, L.F. Reid, D. Ryding, and C.E. Henninger (eds) *Technology-Driven Sustainability: Innovation in the Fashion Supply Chain*. Cham: Springer International Publishing, 2020; 7–25.
Publisher Full Text

Norris L: **Cloth that lies: the secrets of recycling.** In: S. Küchler and D. Miller (eds) *Clothing as material culture*. Oxford: Berg, 2005.

Norris L: **Economies of moral fibre? Recycling charity clothing into emergency aid blankets.** *Journal of Material Culture.* 2012a; **17**(4): 389–404.
Publisher Full Text

Norris L: **Shoddy rags and relief blankets: perceptions of textile recycling in north India**. In: C. Alexander and J. Reno (eds) *Economies of recycling: the global transformation of materials, values and social relations*. London ; New York : New York: Zed Books ; Distributed in the USA by Palgrave Macmillan. 2012b.
Reference Source

Norris L: **Trade and Transformations of Secondhand Clothing: Introduction.** *TEXTILE.* 2012c; **10**(2): 128–143.
Publisher Full Text

Nørup N, Pihl K, Damgaard A, *et al.*: **Development and testing of a sorting and quality assessment method for textile waste.** *Waste Manag.* 2018; **79**: 8–21.
PubMed Abstract | Publisher Full Text

Pailthorpe M, Wood E: **Notes- Topic 15 - Principles of Wool Fabric Finishing**. Woolwise - Australian Wool Education Trust. 2012; (Accessed: 28 May 2020).
Reference Source

Payne A: **6 - Open- and closed-loop recycling of textile and apparel products**. In: S.S. Muthu (ed.) *Handbook of life cycle assessment (LCA) of textiles and clothing*. Cambridge, England: Woodhouse Publishing (Woodhead publishing series in textiles, number 172). 2015; 103–123.
Publisher Full Text

Ragaert K, Delva L, Van Geem K: **Mechanical and chemical recycling of solid plastic waste.** *Waste Manag.* 2017; **69**: 24–58.
PubMed Abstract | Publisher Full Text

Rogers M: **Contextualizing Theories and Practices of Bricolage Research.** *The Qualitative Report.* 2012; **17**(48): 1–17.
Publisher Full Text

Roos S, Sandin G, Peters G, *et al.*: **White paper on textile recycling**. 2019: 09. RISE IVF AB: Mölndal, Sweden, 2019; 58. (Accessed: 6 January 2020).
Reference Source

Runnel A, Raihan K, Castle N, *et al.*: **The Undiscovered Business Potential of Production Leftovers within Global Fashion Supply Chains: Creating a Digitally Enhanced Circular Economy - Insight from research among fabric and garment factories of China and Bangladesh**. Reverse Resources, 2017; (Accessed: 28 March 2021).
Reference Source

Sakthivel S, Ramachandran T, Chandhanu R, *et al.*: **Development of products using reclaimed fibres.** *Indian Textile Journal.* 2010; **121**(1): 24–33.

Sinclair R: **Textiles and fashion: materials, design and technology**. Boston, MA: Elsevier, 2014.
Publisher Full Text

Swain J, King B: **Using Informal Conversations in Qualitative Research.** *Int J Qual Meth.* 2022; **21**: 16094069221085056.
Publisher Full Text

Syrett H, Gonza S, Sawers C, *et al.*: **Scaling Circularity: Lessons learned from the Circular Fashion Partnership for building pre-competitive collaborations to scale upstream circular fashion systems**. Copenhagen, Denmark: McKinsey & Company and Global Fashion Agenda. 2021; (Accessed: 22 November 2021).
Reference Source

Tanttu M, Kohtala C, Niinimäki K: **Can Design-Driven Material Innovation Also Drive Circularity?** In: *Circular Transitions Proceedings*. London, UK: Centre for Circular Design, 2016; 20–31. (Accessed: 27 February 2020).
Reference Source

Tufte ER: **Envisioning information.** Cheshire, Connecticut: Graphics Press, 1990.

Uchimaru M, Kimura T, Sato T: **Study on Recycling System of Waste Textiles based on Colour.** *J Texture Eng.* 2013; **59**(6): 159–164.
Publisher Full Text

Vadicherla T, Saravanan D: **Effect of Blend Ratio on the Quality Characteristics of Recycled Polyester/Cotton Blended Ring Spun Yarn.** *FIBRES & TEXTILES in Eastern Europe.* 2017; **25**(122): 48–52.
Publisher Full Text

Vuletich C: **Sustainable Textile Design as Bricolage**. MISTRA Future Fashion. 2014; (Accessed: 1 August 2022).
Reference Source

Wijnia G: **Mapping obsolete inventory in the Dutch apparel industry: A**

qualitative and quantitative analysis of discounted and unsold volumes in apparel. MSc Thesis. Wageningen University - Department of Social Sciences. 2016; (Accessed: 12 July 2022).
Reference Source

Yee JSR, Bremner C: **Methodological Bricolage - What does it tell us about Design.** In: *Proceedings of the Doctoral Design Education Conference*. Hong Kong.: Hong Kong Polytechnic, 2011; 11. (Accessed: 11 September 2020).
Reference Source

Open Peer Review

Current Peer Review Status: ✔ ✔

Version 1

Reviewer Report 06 February 2023

https://doi.org/10.21956/materialsopenres.18753.r26827

✔ **Claire Lerpiniere**
Textile Engineering and Materials (TEAM) Research Group, School of Fashion and Textiles, De Montfort University, Leicester, UK

This paper illustrates a real-world application of theory and frameworks for evaluating and colour sorting knitted garments for recycling and fibre recovery, an ongoing issue which requires resolution if the industry is to transition to circular economic principles.
In particular, the proposed methods create a bridge between scientific fibre recycling and design processes, and therefore have multiple applications in the wider context of the circular economy.
The research method of interviewing experts in the industry is valid, and ethical clearance was granted prior to conducting the research.

Is the work clearly and accurately presented and does it engage with the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Textile design, fashion and textiles manufacturing, the circular economy, textile fibre properties, structure, and recycling.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 21 December 2022

https://doi.org/10.21956/materialsopenres.18753.r26824

Kirsi Niinimäki
Design Department, School of Art, Design and Architecture, Aalto University, Espoo, Finland

The study is timely and topic is connected to the emerging field of materials and material design in a circular economy context. Therefore this research contributes well to knowledge gap existing in textiles circularity. The research uses quite experimental methods but this approach is quite suitable for research through design context. Bricolage of methods is described, but bricolage as such is also a research method which could have been used here. The research combines textile engineering and textile design methods ending up prototypes of yarns and their content description. In all the study makes clear scientific contribution.

Is the work clearly and accurately presented and does it engage with the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
No source data required

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Sustainable fashion and textile design, fashion and textiles in a circular economy

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.