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QUANTIFYING CIRCULARITY: TOOLS AND INSIGHTS FOR FASHION DESIGN FOR RECYCLING.

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ABSTRACT | The reduction in carbon emissions achieved in this decade will be crucial to limiting climate change and the threat it causes to people and planet (Calvin et al., 2023). To contribute to a transition to net zero, the textile and fashion industry must urgently decouple itself from the use of virgin resources (Sadowski, Perkins and McGarvey, 2021). As put forward by WRAP's Textiles 2030 roadmap, the use of recycled fibres is a key leverage point to reduce impacts including CO2 (WRAP, 2021). However, the textile-to-textile recycling system is currently fractured by the inadequate design of garments. Most garments on the market are not designed for recyclability, and even when they are, they are difficult to identify as such. To limit entropy in the form of material waste, it is therefore urgent that all new clothes should be designed for recycling and clearly labelled for efficient collection.

McKinsey's Scaling Textile Recycling in Europe (McKinsey, 2022) report highlights that real collaboration is needed for the textiles value chain to reach the critical scale needed to provide sufficient feedstock for fibre-to-fibre recycling technologies. Building on previous research providing 'insights for designing with future garments with full recyclability in mind' (Goldsworthy et al, 2019, p47, Hornbuckle et al, 2023, p11) the Quantifying Circularity project brings together partners from both sides of the garment circularity equation: brands and recyclers. The research is carried out by academic and industry go-betweens who bridge the divide between technical recyclers and creative brands. Importantly the project also brought environmental analysts into the process to apply LCA methods to better 'understand the environmental impacts of design decisions' (Goldsworthy et al., 2017, Goldsworthy and Ellams, 2019, Forst et al., 2023). The project aims to develop tools to facilitate the access to specific recycler parameters in the early stages of the design process.

This paper will present the insights from developing and testing guidelines to support designers in embedding recyclability within each product of their collections. The guidelines were tested and refined through three workshops carried out with fashion and textiles brands across the UK. These collaborative sessions produced a range of garment concepts that offered solutions to current recyclability challenges. Across the wide range of brand type and size, some common challenges were identified. These issues highlight the need for a systemic approach to recyclability, one that addresses both the detailed scale of trims as well as shifting agendas and complex communications between stakeholders in the field.

1. Net-Zero Objectives for Fashion

1.1 A Circular Textiles Economy

The fashion and textiles industry is a substantial contributor to the environmental harm generated by human activity (Waste and Resources Action Programme, 2012). To remain within planetary boundaries and work towards the Paris Agreement, it is widely acknowledged that it must undergo rapid and radical change (Amed et al., 2022; World Economic Forum, 2022). Sustainable design practices must be implemented across the entire sector, whether with micro and small fashion brands or large multinational retailers. Reducing impacts through green energy and non-toxic processing is key, but the waste created by manufacturing and consumption and the impacts that come with it must also be addressed. A part of reducing the impacts of fashion on the environment is to transition to a circular textile economy (Ellen MacArthur Foundation, 2017). This includes multiple strategies that enable sustainability, including designing for product longevity, but also importantly designing for materials to be recovered at the end of life to be made into new products of equivalent value.

Research estimates the apparel industry produces approximately 93.1 million tonnes of textile waste annually (Quantis, 2018), yet only 0.5% of global fibres are from recycled pre- or post-consumer textiles (Textile Exchange, 2020). Closing the loop on textiles is a key component of net-zero objectives. As pointed out by WRAP, the diversion of textile waste from landfill and incineration and its use as a secondary resource in the production of new garments is key to achieving targets for decarbonisation (WRAP, 2021). However, there exist multiple challenges to the efficient recovery and recycling of textiles at end of life.

1.2 Design for Recycling

Currently, clothing is not circular because it is not designed to be recycled. Design for recycling is a fundamental principle of circular design that needs to be implemented in all products to achieve the needed shift in the industry. It entails an understanding of end-of-life trajectories for the materials and products that are put on the market today. Initiatives such as the ‘Jeans Redesign Challenge’ (Ellen MacArthur Foundation, 2021) show the enthusiasm for circularity in fashion, but in order for future clothing to be fully circular it must be ‘designed for defined recycling processes and technologies’ (Hornbuckle et al., 2023, p11). Rules such as mono-material design, limiting disruptors and adequate labelling are all key to enabling an uninterrupted flow of resources in a circular economy.

Designers hold a key role in this transition to circularity, it is therefore key to put the tools and knowledge concerning recycling at their disposal, but these tools are not static recommendations. They need to align with the development of recycling technologies as they progress. The quantifying Circularity project thus aims to provide clear and concrete guidelines for design for recycling with input from the recyclers at every stage. Garments are produced based on existing frameworks without this connection cannot guarantee success. The novel angle of this project creates circular design principles on specific and targeted capabilities of fibre-to-fibre recyclers. If we work ‘with recycling science to set the brief for recyclability’ at the outset we improve our chances of success significantly (Goldsworthy et al., 2019, p23).

One major challenge when taking on this approach is the current underdeveloped state of the textile-to-textile recycling sector. While change is happening fast, most recyclers are still in the teething phase of the development of their technology, with key innovation still at pilot stage. While technically textile to textile recycling is completely possible, there are still systemic issues to overcome for garments to be recovered, identified, sorted, and recycled so that they can become fibres in new garments. Much of circular design, including the work presented here, is pre-empting the full optimisation of the recycling system to contribute to its development.

1.3 The Circular Textiles Foundation

From the learnings of setting up the Plan B textile-to-textile thermo-mechanical recycling technology and company, the Circular Textiles Foundation emerged as an answer to the systemic issues slowing down the shift to circularity in the textile industry. The work described is based on the CTF's identification of challenges and opportunities for circularity in fashion. Developing recycling technology is necessary, but will only achieve impact at scale if products are designed to comply with the, sometimes quite strict, parameters for acceptability.

The CTF acts as a spokesperson for recyclers across the world, collecting the most up-to-date information on what input can be accepted for mechanical or chemical recycling. They translate this information into training and support for brands wishing to embark on a circularity journey, addressing the challenges of the current discrepancy between product design and recycling parameters.

1.4 The Textiles Circularity Vision

The overarching aim of the Quantifying Circularity project is to contribute to a shift in circularity across the textile industry, but its focus is on design for recycling. This means that several assumptions about other parts of the system are made. Other aspects of the system including customer behaviours, collection sorting and pre-processing are assumed to work optimally in a best-case scenario configuration. While it is known that improvements are needed in these segments of the system, they are out of scope for this study.

In the vision for circularity represented by this work, garments are collected from the user after a long use phase. The post-consumer waste will then be identified as either fit for resale or non-re-wearable. The non-re-wearable fraction can then be identified for recycling routes. Any garment designed for recycling could be singled out as such thanks to the CTF logo, once recyclability has been noted, the sorter can determine what type of recycling is most adequate by using hand-held spectroscopic devices which can tell what type of fibre the garment is made of even if labels have been removed. These devices are seen as a key contributor to circularity at the sorting stage (Circle Economy and Fashion for Good, 2022) and will work alongside certification to channel end of life garments to the right recycler. Once the fibre type is identified, the garments are aggregated into the recycler category, with for example white 100% cotton garments destined for mechanical recycling and garments with 5% contamination to 95% cotton destined to chemical cellulose recycling. Those products can then be pre-processed to remove any unavoidable disruptors and shredded to fit the recycler's specifications. The input is then processed in the appropriate technology and made into fibres or yarn that replace the need for virgin fibres in the design of new products. The project's aim is to provide the best possible guidelines and support for the design of products that can travel smoothly and efficiently through this system to be recovered for recycled fibre production.

2. Cross-Sector Collaboration

2.1 Recyclers Advisory Board

Setting up an advisory board with a selected panel of recyclers anchors the project in the specific criteria for recyclability. Currently, much of the work that is done on educating designers and brands in terms of circularity is based on generic recommendations. When exploring the specific criteria for each recycler it becomes apparent that finer detail is key to enabling true circularity.

The recyclers integrated to the project represent a range of technologies and development stages, offering a holistic perspective of possible end of life trajectories for post-consumer garments. Mechanical recyclers of cotton and wool show the options for historic and well-established fibre to fibre recycling, whereas chemical recyclers of cellulosic fibres demonstrate an area in development but with solutions already at

scale. The thermo-mechanical polyester recycler included in the project opened the first ever at-scale textile to textile recycling machine during the project timeframe. And finally, a mixed fibres chemical recycler currently at pilot scale shows options for the future of the sector.

A challenge to acknowledge when working across this range of recycling stakeholders is that the different technologies are not all optimised to the same level, and it may appear as though some are much more efficient in terms of energy and water use than others. While there is a difference between mechanical and chemical processes, the maturity of the technology must be taken into account and allowances for progress with wider take-up must be made. The restrictions for input to each of these processes also vary. Chemical processes generally accept more contamination than mechanical processes making them look favourable to brands designing for circularity. While the chemical process allows for the extraction of contaminants, the process to break the material down takes more energy and chemical inputs than a mechanical process which retains all contaminants in the recycled output. This points to the need for a concerted effort amongst recycling stakeholders to realise the vision for textiles to cascade from low impact processes to more comprehensive deconstruction in successive garment lifecycles. In this model the different recycling technologies don't compete but complete each other.

2.2 Brand Participation

Circularity principles need to be adopted across the full value chain. However, it can sometimes be difficult for brands in the fashion sector to see the value of design for recycling as the end of life of the garments they produce is often beyond their control or horizon. The project builds on networks of proactive fashion companies which see circularity as an essential part of their sustainability commitments.

Participants in this research have provided valuable perspectives on the types of products in their ranges which can be designed for recyclability and what challenges persist when operating this shift. By participating in workshops as cohorts of brands, they have generously contributed to the progression of circular design strategies. Increasing knowledge of circularity in the industry will come through more brands allocating time to training such as that offered in the QC project, understanding what methods and language are most adequate to onboard key stakeholders in part of the insights from this work. Part of the impact and legacy of this project lies in the onboarding of brands which hold the keys to an industry-wide transition to circularity. The connections between the organisations involved in this collaboration is designed to extend beyond the project timeframe.

2.3 WRAP Perspective

The Waste and Resources Action Programme is a UK non-profit working towards sustainability and circularity in a range of sectors. With the Textiles 2030 Roadmap, the organisation is galvanising the fashion industry to achieve net-zero targets in the UK. Textiles 2030 is a voluntary agreement to change practices and move towards sustainability through design for circularity, new business models, closing the loop on materials, and encouraging consumer behaviour change. WRAP's involvement in the Quantifying Circularity project stems from the development of the Textiles 2030 Footprint Calculator. This tool offers a simplified LCA method to support brands in assessing and amending their impacts through a review of their fibre use across their full product range, and the modelling of the effects of improvement strategies on their carbon, water, and energy impacts. The calculation of the impact savings afforded by design for recycling will expand the footprint calculator work with a focus on circularity and carbon calculation. The approach provided by WRAP contributes to making the guidelines for recycling specific and truly understanding the quantified implications of different trajectories at the end of life.

3. Quantifying Circularity

3.1 Workshops to Apply Design for Recycling

The project is structured around four workshops taking place in various UK locations offering more accessible opportunities to brands near their headquarters. At the time of writing, three of the four events have taken place. Plymouth, London, and Kettering saw each four or five brands joining for a full day of learning and work on the topic of circularity. A final workshop in Manchester will close this programme of in-person events. Insights on the most effective communication approaches and best prompts to encourage creativity in the redesign activity were taken on after each iteration and included in the design of the following session.

Each workshop followed a similar pattern by introducing participants to the notions and imperatives of design for recycling, showing successful case studies of brands having taken on such an approach as inspiration. The brands worked in groups amongst themselves to get in-depth perspectives on the products brought to the table. Working through the step-by-step redesign activity with three garments in turn led to seeing the different challenges based on various types of garments. A final round of presentations by each participant group allowed us to see the range of challenges across brands. While some garments were deemed impossible to redesign without compromising the brand's sales, other redesigns were seen as very easy switches that could be taken on almost immediately with no price increase or big changes to the product style. In multiple cases, brands realised that while the products they had brought to the workshop, presenting what they saw as an interesting challenge to address, were too difficult to design for recycling, the lessons they learned during the day could apply to other products in their range that could be 'easy wins'. Overall, the participants left feeling empowered to change the way they design to enable more circularity in their ranges.

Figure 1. Quantifying Circularity workshop in London.

3.2 Practical Guidelines for Brands

A key tool for the workshop activities was a practical guide for design for recycling: the three-step recycler identifier. The approach functions on the basis of a redesign exercise (Ellen MacArthur Foundation and IDEO, 2017), where an existing product is taken as a starting point and improvements are considered to make a circular version of it. A key criteria of a redesign challenge is that the key characteristics of the original product such as functionality, aesthetics, and price point should be maintained so that the redesigned version can truly replace the purchase of the original 'unsustainable' product. This means that the designers taking part in the activity need to aptly balance the requirements of recyclers with the product's specifications.

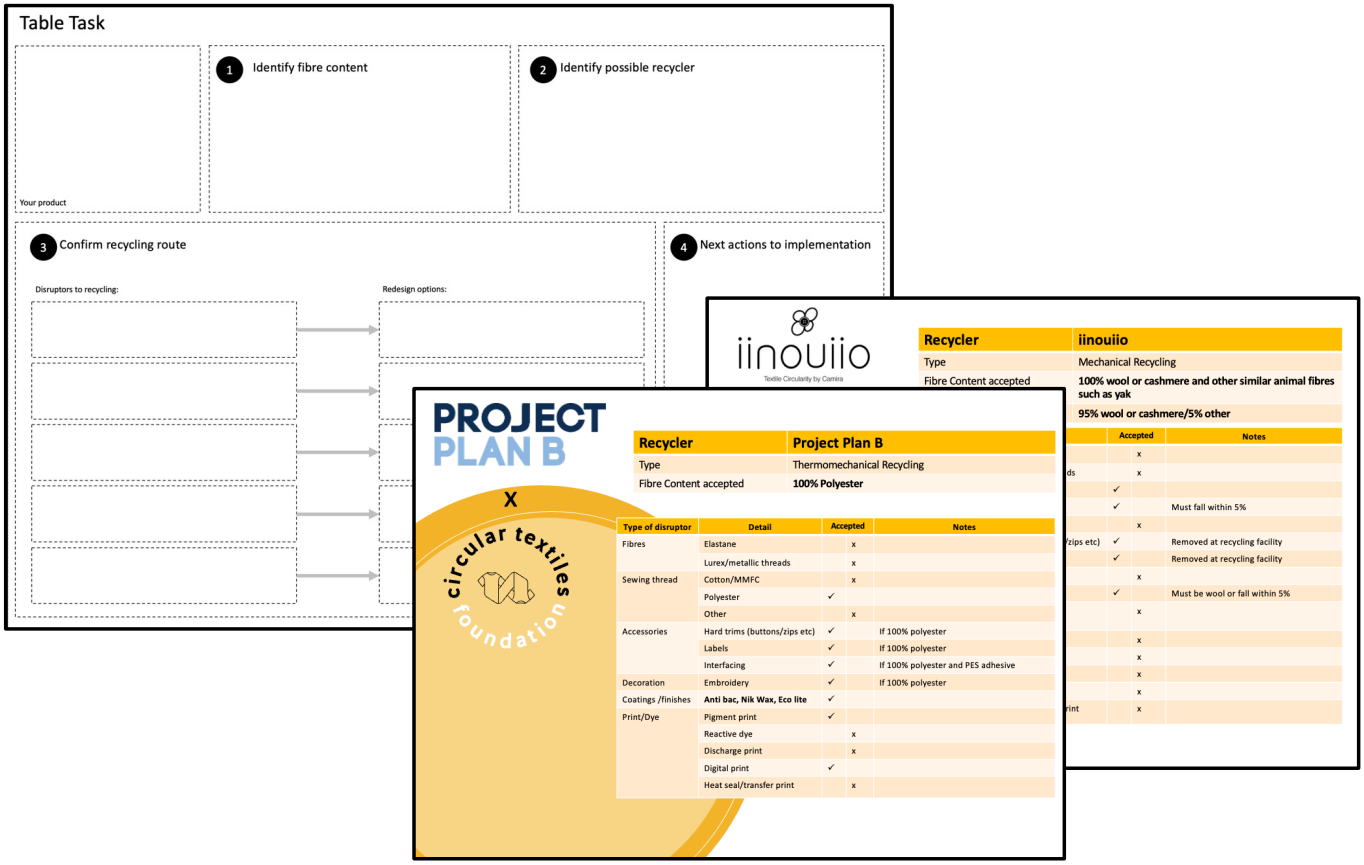

Figure 2. The Quantifying Circularity worksheets guiding workshop participants through the three-step recycler identification process.

The first step to this approach is to identify the garment's main fibre type, this then directs the designer towards the most likely recycler. For example, if a product is mainly made of cotton, they will want to consider either cotton mechanical recycling or cellulose chemical recycling as possible end-of-life options. Once this has been defined, then designers can take a closer look at the specific parameters of the intended recycler. A set of 'recycler parameter' sheets is available as part of the toolkit, each detailing precisely the tolerances for fibre blends, trims, print or coatings for a given recycler. The designers can then identify what disruptors are currently part of the existing garment and discuss how they could be swapped out for alternatives that do not impact the recycling process or simply be removed from the product's design. As an increment from current generic circularity guidelines the instructions are specific to the recyclers involved in the project was created for brands to follow. This allows us to see how features such as prints or trims will impact recycling to various levels.

4. Case Studies of Design for Recycling

4.1 Overview of Case Studies

In each of the three industry-facing workshops which structured the Quantifying Circularity project, the brand attendees were asked to bring three garments from their range. These could be bestsellers or high-volume products that could have a strong impact when redesigned, or more challenging products that represent a key offer from their brand. Alongside the physical product, detailed spec-sheets were provided so that as much information as possible could be gathered on the baseline products. The products that were redesigned ranged from waterproof jackets to wool jumpers, from children fancy-dress to baby pyjamas. A smaller selection of products also represented home-wear ranges. A wide range of product types and recyclability challenges were thus covered.

The redesigned garments form a collection of 32 exemplars showing challenges and opportunities for design for recycling. This collection forms the basis of the analysis presented here. Of the 32 garments reviewed, six were identified as possibly recycled in a thermo-mechanical polyester recycling process, six were seen as destined to both mechanical and chemical cellulose recycling, three as only chemical cellulose recycling, one for wool mechanical recycling, and sixteen could not be attributed to a recycling technology without significant design changes which may affect the product's market value. In the proportion of these latter products, the main reason for their non-recyclability was the main fabric composition, either due to a blend of fibres belonging to different recycling systems (such as cotton and polyester for example), or due to the presence of a large proportion of elastane which is a barrier to all recycling processes. Hard trims such as zips or buttons were identified as disruptors in sixteen garments across all recycling categories, fusing was a disruptor in nine garments, and print was identified as an issue in five garments. This sample thus shows the relevance of various tips for redesigning challenges for recycling.

4.2 Key Challenges in Garment Redesign

The review of the garment redesign case studies provides key lessons that apply across product types when designing for recycling. These must be addressed as a priority and solutions to minimise these disruptors or develop recycling systems to accommodate them must be explored. The challenges laid out here relate specifically to physical components in product design.

Signature sustainable fibres are not recyclable.

Several of the garments brought to the workshops were front-runner products, representing the brand's most forward approach to sustainable design and thus using low-impact fibres or alternatives to cotton and polyester. These fibres often become an important part of a brands identity, for example with linen or bamboo viscose products being a sign of quality and sustainability in the customer's eye. However, as the recycling sector is still in development, the current focus is on fibres that represent a majority share of the market. Thus viscose-like fibres and bast fibres, while not technically impossible to recycle, will not be accepted by any recycler for the foreseeable future. The challenge to brands is then to balance sustainable design with the choice of alternative fibres, and circularity which focuses on more common resources.

Removing trims makes the product less attractive.

Removing disruptors to recycling formed the basis of the garment redesign, yet in some cases, removing these elements can collide with the product's identity or functionality. Fusing for example, can be easily be reconsidered with no visible changes to the user, but for elements like pocket zips, removing them would diminish the product's functionality, meaning that the redesigned version would not fully replace the functional unit of the original version. The baseline for a redesign exercise is that the product that is

redesigned should fully replace the original version. If there are discrepancies in terms of look, functionality, or price point, them it is likely that the customer will fulfil their need at their expected budget point with another product and dismiss the sustainably redesigned option.

Stretch is a challenge across a wide range of products.

It is widely known that elastane is a strong disruptor for all recycling technologies (Östlund et al., 2017). While it will end up as waste in chemical recycling processes, in mechanical processes, it is a contaminant that negatively affect the output. Yet, stretch is a key characteristic for comfort and elastane is used both as a fibre blend across the base fabric or in trims such as cuffs and waist band elastics. There are currently no alternatives which can be used to provide the same effect without limiting recyclability. In a few of the garment redesigns, the use of elastane was argued as a key contributor to longevity, removing it potentially leading to the garment being disposed of much earlier than if there is some elastane. This connects to the overall discussion on finding a balance between performance and recyclability.

4.3 Systemic Challenges for Circularity

Alongside the issues identified in products themselves, the process of redesigning garments brought up challenges that relate to recycling systems. These will need to be addressed and clarified in tandem with physical redesigns.

Recycler timelines are varied and changing.

Sector-wide circularity will mean that designers will need to integrate the requirements of a range of recycling technologies in their products. The Quantifying Circularity project is one of many endeavours to make these requirements available to decision makers. However, even within the short timeframe of the project, it was noticed that recycler parameters change and need revisions as the technology is tested and scaled. This means that guidelines need to be regularly updated and that the role of mediators between recyclers and brands such as the CTF is key.

In parallel to timeline within a specific recycler's technology development, the difference in development speed between different recyclers also needs to be considered. The policy for certification of recyclability by the Circular Textile Foundation is that garments should abide by the parameters of recyclers that already function at scale and can handle end-of-life garments today. However, many of the solutions for recycling more complex products are currently just on the horizon. The technology has been tested in lab and/or pilot scale, but investment to scale for large quantities is still lagging. The assumption amongst experts is that the clothing designed today will only be collected as a non-re-wearable waste garment in several years, allowing time for the recycling landscape to evolve in the meantime. However, design recommendations today must stick to what is known about available technology and assumptions could have negative effects.

Recycled outputs are not recyclable in turn.

A circular textile economy aims to decouple the production of products from the extraction of virgin resources, effectively using existing materials in infinite loops of recycling. There is much ground to cover before this vision becomes reality, and one challenge is that the output of some of the most promising recycling processes is not currently recyclable itself. For instance, when recycling cotton in a chemical process, the output is a regenerated cellulose similar to viscose. Currently, viscose will not be accepted as input by cellulose recyclers. While the technology and approach of recyclers may evolve in the future, this means that the product of this recycling process will not in turn be recycled which is a challenge to true circularity.

5. Conclusions

5.1 Removing Disruptors and Providing Recyclable Alternatives

A key part of designing for recycling lies in the removal of disruptors. These can take the form of zips, buttons, fusing or sewing thread which is in a different material to the base fabric of the garment and thus acts as a contaminant to the recycled output. Discussion between brands and recycling experts in the Quantifying Circularity workshops led to realise that in some cases, heavy disruptors such as zips or elasticated wastes could not be designed out without impacting the value of the garment. Thus, recommendations to remove trims need to take account of the garment's specifications and functionality. While it must be acknowledged that not all trims are equal, and different redesign strategies may apply, there is also a need for more detail on what can be addressed in pre-processing would support better circular design. The Quantifying Circularity project focuses on product design, but improvements and innovation can also happen in the overall logistics for the sorting and preparation of textile waste. Efficiency of removing some necessary trims could support a more balanced compromise between recyclability and functionality. The library of circular trims developed by the CTF offers a product-based response to this challenge. While not all functions can be performed by trims that are suitable for recycling, selecting lighter elements such as buttons or zips in the same material as the base fabric (generally possible with polyester) can highly increase product recyclability. More research and development is needed in this sector to develop sturdy trims that abide by recycler and sorter parameters. The same goes for elastane, the availability of stretch fibres and elastic trims compatible with polyester and/or cellulosic recycling would be a breakthrough to achieve high product specifications without compromising on circularity.

5.2 Communication Across Actors

Circularity is inherently highly collaborative as all actors from across the sector need to communicate to facilitate the flow of resources. The insights concerning the physical and systemic challenges to recycling presented in this paper are useful to a range of fashion stakeholders from designers to recyclers and policymakers. Working across design research, business support, and environmental engineering in this project has provided a holistic view of recyclability challenges, moving between the hyper-specific level of disruptors, to the general questions relating to systems and logistics. The guidelines and a step-by-step process for designers to follow are framed by this three-pronged vision for circularity. This approach provides designers with clear steps to apply to each product they design in order to enable its future recycling. The next steps for the project are to better frame the benefits of design for recycling over the entire range of a brand's products. Working more closely with WRAP in this next phase, carbon calculations that quantify the assumed benefits of circularity will support a wider change in the industry.

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Kate Goldsworthy is Chair of Circular Design & Innovation and Co-Director of the Centre for Circular Design, based at Chelsea College of Arts. Her core research interests are designing for sustainability, the circular economy and material innovation within textile and fashion contexts. Her methods are transdisciplinary & practice-led, with a focus on fibre-to-fibre recovery and new finishing technologies. This includes more sustainable production systems for the textile industry, and pioneering design solutions for the recycling and recovery of both synthetic polymers and bio-based materials.

Tim Cross has 30 years of experience in garment manufacturing. In the last 5 years, he's been focused on supporting fibre to fibre recycling systems, specifically for post-consumer textiles, as Director of Project Plan B, a thermomechanical textile polyester recycler, in the UK. His work at the Circular Textiles Foundation sees him leading the adoption of circular principles and practices by multiple brands and retailers across the UK.

Jenny Valarino has over 20 years of experience in garment design across womenswear, menswear, and childrenswear. Her experience spans high street to high-end fashion, and her expertise exists across the entire product life cycle. As Head of Circular Design at the Circular Textiles Foundation, Jenny collaborates on circular design solutions to reduce clothing impact. Passionate about using design to tackle industry challenges, she is dedicated to driving change through innovative solutions.

Padouk Fielding brings over 12 years of experience in partnership development and project management, working across multiple sectors, from international development to circular fashion innovation. As Head of Partnerships at the Circular Textiles Foundation, Padouk builds impactful and lasting relationships with brands on their journey to circularity. Padouk is dedicated to driving positive change and firmly believes in the power of strong relationships and collective action.

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