transitions

D2.1 MAPPING TEXTILES AND MATERIALS AND INDUSTRY 4.0 TECHNOLOGY

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1. Executive summary

This deliverable led by WP2 Data Research & Transference provides the mapping of textiles and materials innovations with a specific focus on the circular transition of textile-clothing sector and the mapping of technology and digital tools for textiles & fashion design sectors for an Industry 4.0. The aim of this deliverable is to collect and organize the information needed for the TRASITIONS partners and the project. This document introduces the main innovations that emerged from the mapping developed by NTT and other four partners: ELISAVA, IAAC, NOOF, and HVA.
The list of the collected documentation on which all Transitions partners worked is provided in the paragraph 8 (Bibliography). The complete documentation collected for the mapping is archived within the Transitions drive, which was also reported on the Transitions Miro board.

2. About Transitions

TRANSITIONS (Erasmus + Project) is a strategic alliance for innovation formed by research and technological centers, Vocational Education and Training (VET), Higher Education Institutions (HEI), public policy actors, SMEs, and other sectoral organizations from Spain, Italy, The Netherlands, and Sweden. The aim is to nurture the textile and fashion transition to a 4.0 system and a circular economy by developing new learning methods, tools, and practices to help students, young designers, and professionals face real challenges.
The objective is to create collaborative and real work-based training where the different actors in the value chain work on how to take advantage of technology to generate new value proposals and new business models within a circular economy.
Transitions proposes a multidisciplinary pedagogical approach based on transition design theories and emerging disciplines and practices combining textiles, sustainability and digital technologies.
General objectives:

- To foster new, innovative and multidisciplinary approaches to teaching and learning, fostering innovation in education design and delivery, teaching methods, assessment techniques, learning environments and developing new skills;
- facilitating the flow and co-creation of knowledge between higher education and vocational education and training, research, the public sector and the business sector.

Specifically, TRANSITIONS will:
- Create a modular training programme based on Industry 4.0 for a T&F new circular system.

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- Set up innovation-focused training modules based on real practice and challenges (Transition Labs) to skill, reskill and upskill students and professionals.
- Develop new ways to generate innovation in textile and design processes, production and commercialization.

3. Introduction

The textile and fashion sectors represent two important areas in terms of environmental impact, since the continuous growth production and consumption of textile products has a crucial impact on climate and on water and energy consumption. As reported by the EU Commission in the EU Strategy for Sustainable and Circular Textiles, at the EU level, the consumption of textiles now accounts on average for the fourth highest negative impact on the environment and on climate change, and third highest for water and land use from a global life cycle perspective (European Commission, 2022). This is why it is absolutely necessary to find solutions to limit and reduce the negative impact that the textile and fashion industry has on many areas. The shift of the T&F sector towards a circular business model represents a crucial aspect in order to reduce the impact of the sector on the environment (European Evironment Agency, 2022).
In recent years a gradual, but not easy, green and digital transition of the textile and fashion industry was observed.
The introduced innovations cover many areas, from new types of fiber and materials, recycling technologies, AI, digital tools, and many others.
With this document, TRANSITIONS project aims to map and share the state of the art in textile and material innovation for a circular transition, and technologies and digital tools for an Industry 4.0 transition.

4. Methodology

Deliverable 2.1 Mapping textiles and materials and Industry 4.0 technology presents the mapping result regarding textile and materials innovations and Industry 4.0 technology, essentially based on available bibliography and online resources. The aim is to make helpful information, data, and resources available to textile operators, in particular, those active in the education sector. Also, the mapping presented in this document may be a valid tool to support the daily business of textile researchers and industry operators.
The Transitions partners that worked on the creation and elaboration of the mapping are:

- NTT[1] - Next Technology Tecnotessile
- Elisava[2] - Barcelona School of Design and Engineering
- IAAC[3] – Institute for Advanced Architecture of Catalonia
- NOOF[4] - New Order of Fashion
- HVA [5] - Amsterdam University of Applied Sciences

The Transitions partners worked in multiple steps through a co-design process to organize the information gathering and mapping activity.
The collection of material was carried out in several stages. An initial online session was organized with the partners to define the thematic areas to focus on and which approach to use in mapping. "Keyword focus areas" were identified and included in the mapping development for a dual purpose: to identify the areas on which the mapping was developed and to indicate the areas of interest, and to create tags within the Excel table to indicate the subject matter of each document collected for the categories to facilitate the work.

A second online session was organized to categorize the documents collected within the Miro Board platform. Based on the "Keywords focus areas," the partners outlined the areas identified for the mapping of Textiles and Materials innovation, which are:

- Circularity
- Natural Fibers
- Bio-based fibers
- Zero-waste challenges

[1] https://www.tecnotex.it/
[2] https://www.elisava.net/
[3] https://iaac.net/
[4] http://www.neworderoffashion.com
[5] https://www.amsterdamuas.com/

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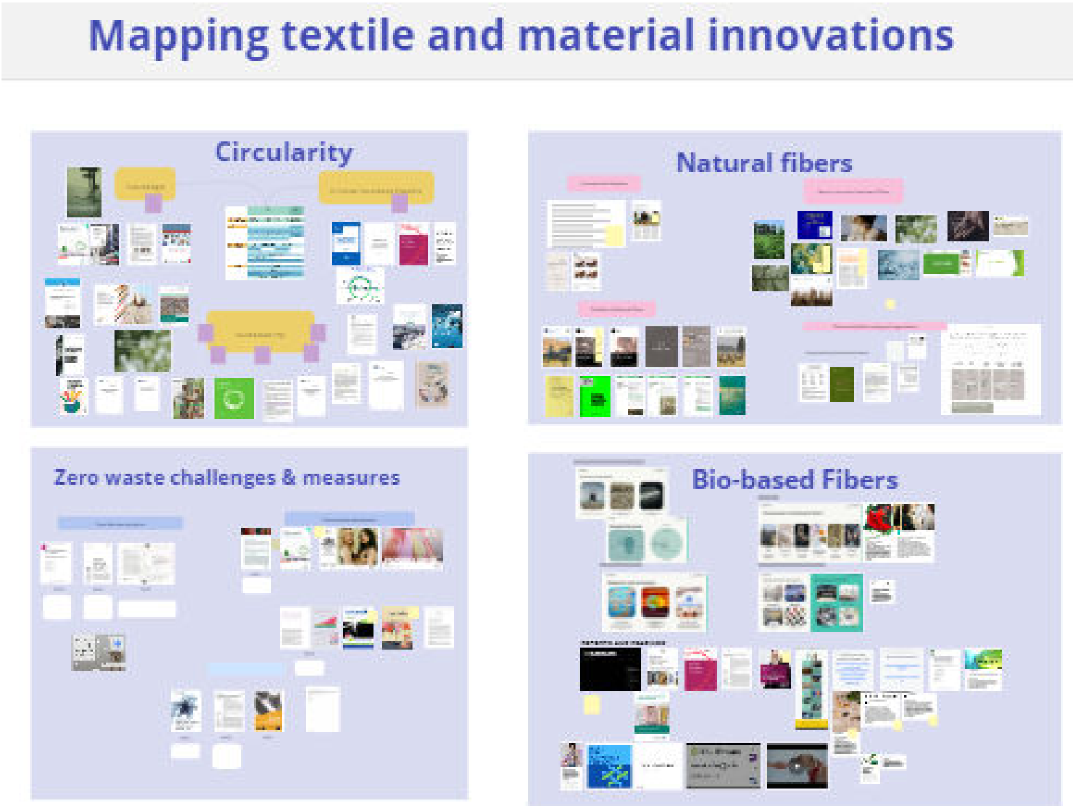

Figure 1 – Mapping of the textile and material innovation in the Transitions Miroboard

The areas identified for the mapping of Industry 4.0 technology are:

- Artificial intelligence, Big Data, and Automatization
- Track and trace and blockchain
- Augmented and virtual reality
- Smart Textiles & Wearables
- Open-source hardware and low-tech systems
- Recycling technologies
- Digital prototyping and additive manufacturing
- Dyeing and post-processing

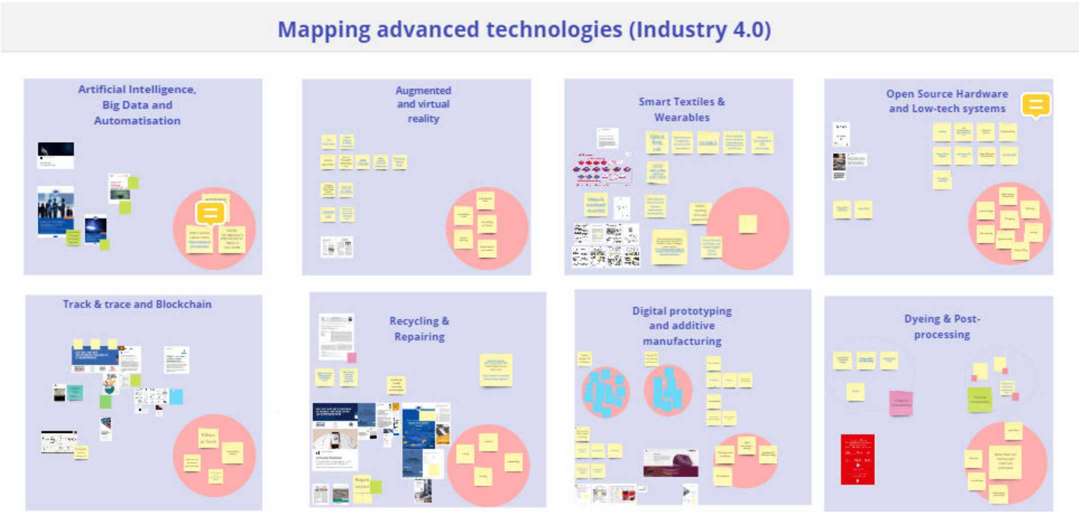

Figure 2 – Mapping of the advance technologies in the Transitions Miroboard

One of the aims of the Transitions project is to map current trends in textile and material innovation to support the transition of the sectors towards a circular economy.
This report presents innovative textile solutions that could contribute to this transition and are in line with the upcoming legislation at the European level.

In the following chapters, we will present the main innovations in materials and technologies for Industry 4.0 analyzed due to the mapping carried out by Transitions partners. An analysis of the level of innovation (in light blue) and circularity/sustainability (in blue) of materials and technologies detailed in the following chapters is shown in the following chart. The level of innovation and circularity/sustainability is rated on a scale of 1 to 10, where 1 stands for "not at all innovative – circular/sustainable" and 10 stands for "very innovative – circular/sustainable.

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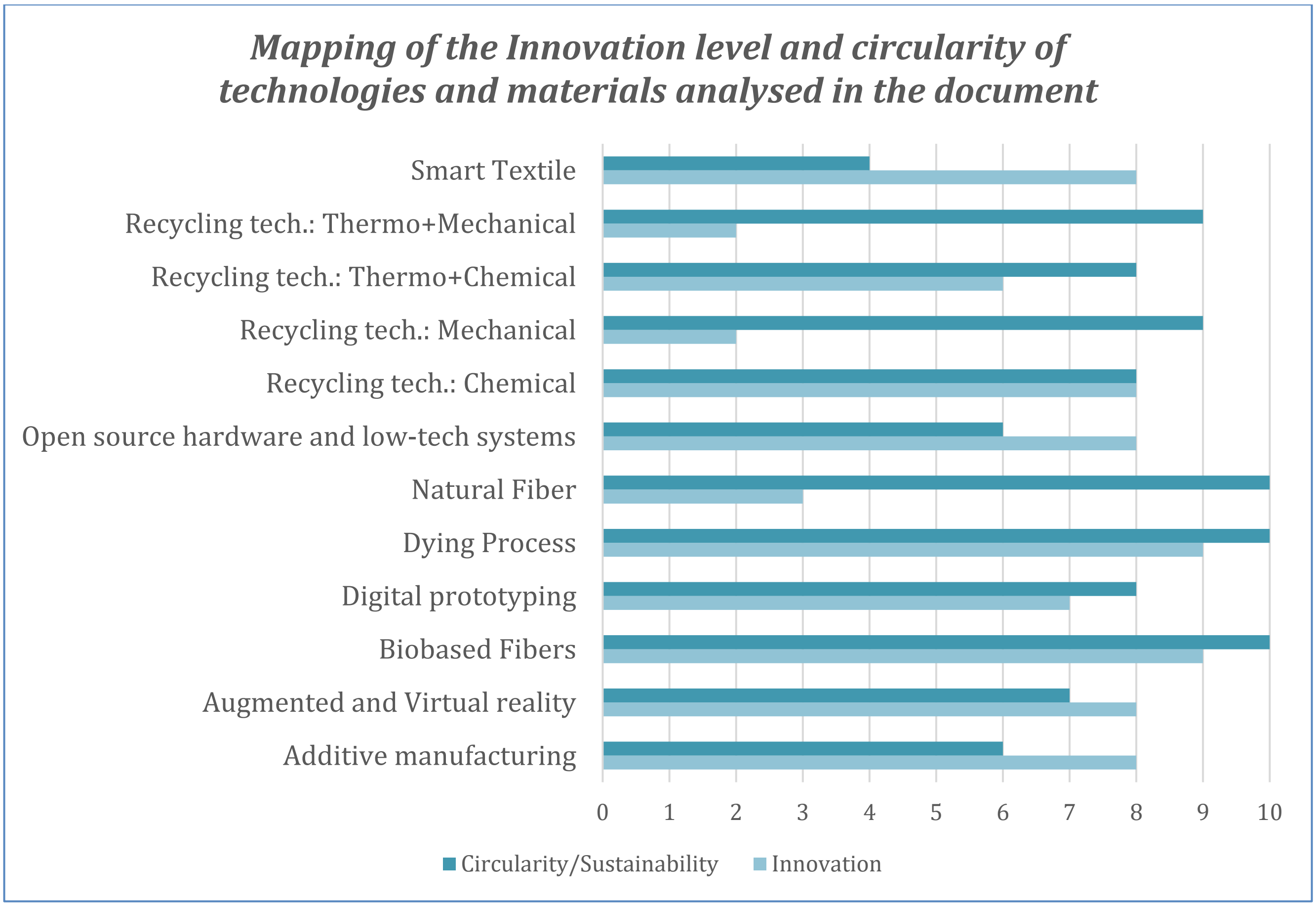

Figure 3 - Preliminary overview of the level of sustainability and innovation presented in the report

4.1. Foster greater circularity in the textile and fashion industry

There is a pressing need for a significant change in the textile and fashion industry. The fast fashion industry has grown significantly in the past 20 years due to cheap, synthetic materials and moved production to places with weak labor and environmental rules. To make a real change, companies should consider different aspects that can permit the reduction of the industry's impact on the environment.

In the following paragraphs, this document will provide an overview of the possible elements that could become drivers of change.

4.1.1. Circular Business Models

The shift of the T&F sector towards a circular business model represents a crucial aspect in order to reduce the impact of the sector on the environment (European Environmental Agency, 2022). Such a shift would mean moving beyond the current linear economy approach, with limited focus on resource reduction, reuse, and recycling, to a model characterized by sustainable and circular practices (Moreira et al.; K., 2022).

Circular business models are part of the various types of business models and exist in the same field to the extent that they also overlap on some points with sustainable business models. What characterizes a circular business model is that it will focus on dematerializing, closing, slowing, and narrowing down resource loops.

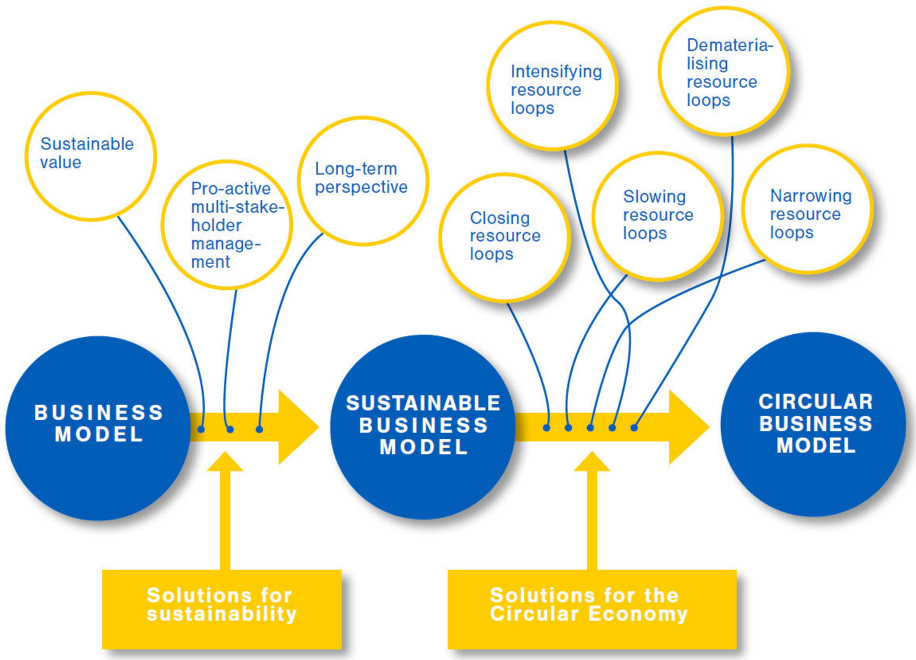

Figure 4. Comparison of traditional, sustainable, and circular business models. Source: Moreira, N., & Niinimäki, K., 2022.

The white paper "Circular Business Models In The Textile Industry" (Moreira, N., & Niinimäki, K., 2022), presents the most discussed models in academic literature and professional publications. Innovation is the key within each circular business model which "incorporates elements that slow, narrow, and close resource loops" (Moreira, N., & Niinimäki, K., 2022, p. 8), thereby decreasing the amount of resources produced and minimizing waste and emissions leakage.

- **Product and use-oriented:** This category of circular business models is among the most common, being a sector strongly based on the final, physical product. This model focuses on Circular Product Design, Design for Recycling or Intentional Design, Product-Service Systems, Resource Recovery, Use, Reuse, Share and Repair.
- **Service and data-oriented:** This group of business models is yet to be common in the textile industry, but it is increasingly seen as a solution to overproduction and to decrease the distances caused by the COVID pandemic.
- **Production-oriented:** It envisages the use of the residual products of the process itself as raw material for other processes through industrial symbiosis, a relatively new concept based on a mutual exchange between the parties involved, a kind of industrial cluster in which the outputs of production can become the inputs for another (usually geographically close) plant. Otherwise, business ecosystems are promoted, partnerships that are built independently of the location of the partners, focused on innovation and knowledge exchange.
- **Result-oriented:** They focus mainly on the result of the model and how to achieve it. It focuses mainly on production on-demand, extending the life of a product through design, repair, upgrade, and resale, and designing products with the goal of being repairable, upgradeable, reusable, and easily disassembled (Moreira, N., & Niinimäki, K., 2022).

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Figure 5. Circular Business Models Matrix. Source: Moreira, N., & Niinimäki, K., 2022.

4.1.2. Design for circularity

The design stage determines up to 80% of product environmental impacts. This represents a crucial step in the textile sector's transition to a circular system of production and consumption. For this reason, the circular design of textile products plays a key role in this transition: it aims to design products to improve their durability, reparability, and recyclability and to ensure the use of secondary raw materials in new products. For this reason, carefully selecting materials at the design stage is crucial for implementing a circular economy. The European Environmental Agency identifies circular business model pathways that could support the transition of textile and fashion sectors towards a circular system. In all pathways, the design phase plays a critical role.

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In the last 20 years, the use time of clothes has decreased by 36%. The first circular business model pathway is to ensure the longevity and durability of textile products. Designing products with higher durability allows and supports more prolonged product use, extending the life cycle of textiles.
For this reason, the selection of materials at the design stage is crucial to increasing the longevity, durability, and repairability of textiles. In addition, to ensure higher material durability, it is essential to create an emotional connection between the consumer and the garment through timeless design (slow fashion), information on product care, and the offer of garment repair services.
Eco-design can also play a strategic role in the production stage, optimizing resource use. It means reducing emissions, waste, and inputs like water, chemicals, and energy and using renewable sources and/or recycled content (European Environmental Agency, 2022). Another pathway in which design plays a role is the collection and reuse of textiles. All these pathways focus on s*lowing down the loop*; contrary to them, the last pathway on recycling and material reuse focuses on "closing the loop" by considering the recyclability of textiles in the design process.

However, designing for circularity and, more generally, implementing a circular business model is closely linked to, and even dependent on, consumer behavior and policy choices. In order to slow down and close the circle to make it circular, all these aspects need to intervene and move towards a more circular sector (European Environmental Agency, 2022).

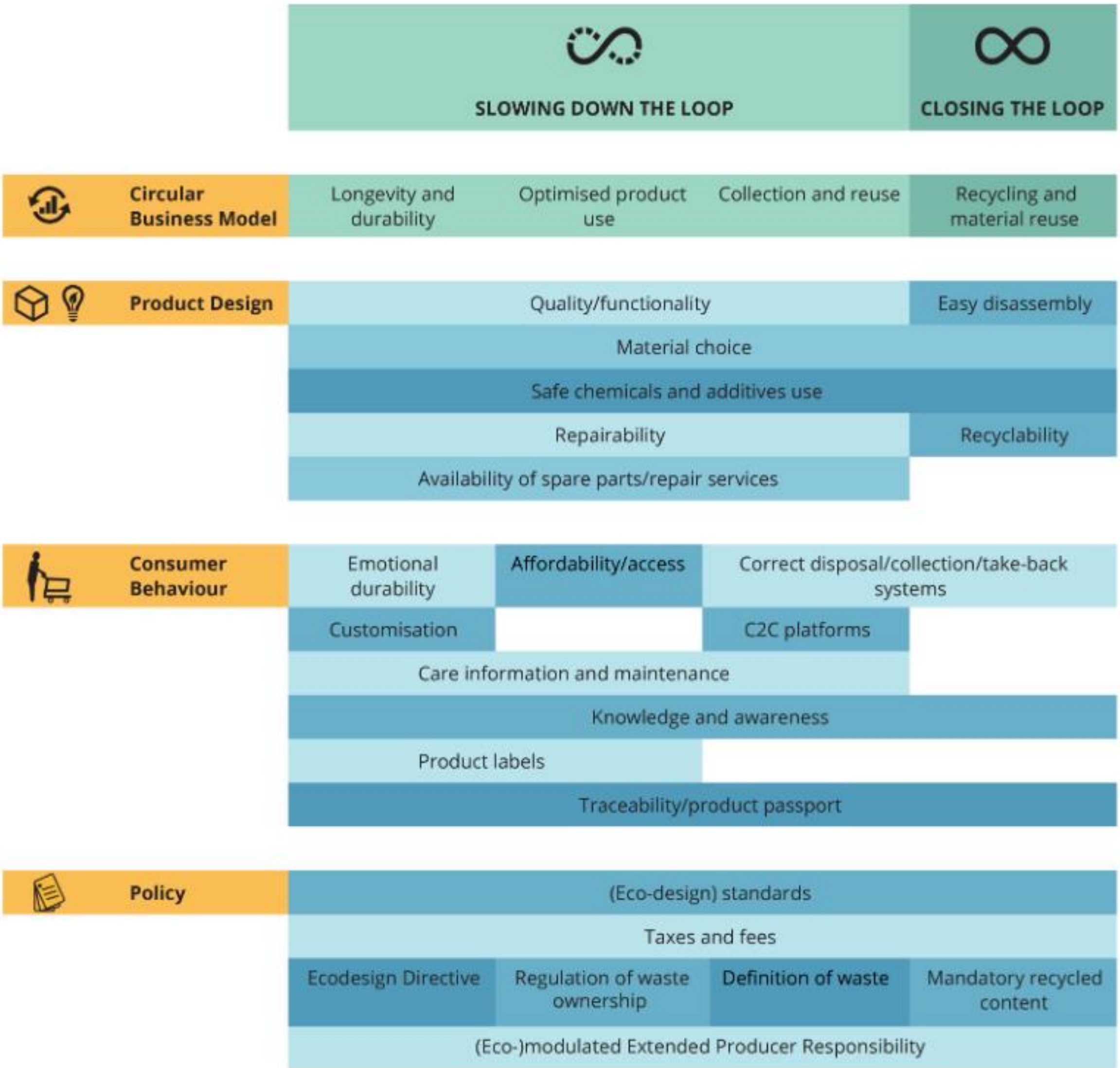

Figure 6. Overview of linkages between the circular business model, product design, consumer behaviour and policy. Source: European Evironment Agency, 2022.

4.1.3. Consumer behavior and policy choices

The Extended producer responsibility (EPR), an obligation under EU waste legislation to establish a separate textile waste collection, becomes effective from 1 January 2025. As brands move towards this acceptance of responsibility across the supply chain, designers across all fashion and textile market segments will have to design differently – they must start to design for low impact, reuse (multiple users), repair, and recycling (Botta and Cabral, 2021).

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Another significant change that the upcoming EU legislation will bring forward is the Digital Product passport; this will enable the consumer to make conscious choices by having plenty of relevant information about the product he/she is buying available. This information will drive the consumer in the purchase process and will help more sustainable and circular approaches, both for production and consumption. Such new approaches will bring along the need to track and trace on the producer side and to adopt transparent internal policies when manufacturing a textile good.
The same can be said about the "Sustainable by design" directive, encompassing:

- Developing design technologies for better environmental performance of textile products;
- Technologies for more durability, reliability/reusability, reparability, recyclability and fewer substances of concern;
- Increase in mechanically recycled content and remanufacturing/upcycling, and less microplastic/microfiber emissions from washing and using stage.

The directive about "Sustainable by design" will consistently contribute to the creation of new products and, hence, to the adoption of more circular business models.

4.2. Zero waste challenges

This section of the report addresses the zero-waste definition, main measures, strategies, policy recommendations, and existing legislation, drawing mainly from Zero Waste Europe, several European reports, and the latest published works within the European academic textile and fashion design community.

4.2.1. Zero Waste in the Textile and Fashion Industry

In the following paragraphs, we summarize the vision for a zero-waste fashion industry developed by Zero Waste Europe in their paper "A Zero Waste Vision for Fashion. Chapter 1: All We Need Is Less" (Mörsen, T., 2023).

According to the Zero Waste International Alliance, Zero waste is the practice of responsibly producing, consuming, reusing, and recovering products, packaging, and materials, all while avoiding any form of incineration and preventing any discharges into the environment, be it land, water, or air, which could pose threats to both the ecosystem and human well-being.

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There is an urgent need for the EU and national governments to avoid the triple planetary climate change crisis, pollution, and biodiversity loss. While the shift to a circular economy within the fashion industry has been proposed as a solution, it has limitations. It is essential to reduce material use and adopt sufficiency principles significantly. The fast fashion industry is a significant contributor to environmental issues, and a substantial emissions gap will remain until 2030, even with expected efficiency improvements. We need calls for active government intervention at various levels to avoid this.

According to the Zero Waste Europe vision, governments and decision-makers should focus on three key areas of intervention to align the textile sector with environmental sustainability goals. Effective action requires a strategic combination of these measures:

1. **Setting Legal Boundaries at the EU Level:**
   - To mandate a ban on destroying unsold goods by large enterprises, as recently supported by the European Parliament.
   - To establish concrete targets for textile waste reduction to drive policy measures in Member States, aiming for a one-third reduction in textile waste by 2040 compared to 2020.
   - To introduce a target for primary resource use, transforming EU waste legislation into a "Resource Framework Directive" in alignment with the 1.5-degree target.

2. **Using Financial Incentives**
   - To expand Extended Producer Responsibility schemes for fast fashion producers to address waste generation by incorporating prevention, repair, and reuse measures.
   - To apply EPR as a tax based on the number of items placed on the market, rewarding circular business practices.
   - Extend environmental taxes, especially virgin materials like plastics, and complement them with social programs like a Carbon Fee and Dividend scheme.
   - Utilizing the EU's taxonomy process to direct investments toward zero-waste businesses, ensuring it prevents greenwashing and promotes eco-friendly investments.

3. Fostering a culture of sufficiency:

Fostering a culture of sufficiency is essential for promoting sustainable lifestyles. A culture of sufficiency involves discouraging overconsumption, particularly in the fashion industry, where the business model encourages continuous purchases of new trends. While determining what constitutes enough clothing remains a subject of ongoing research, public policy can shape consumer behavior.

Actions to promote sufficiency include:

- Disincentivizing Overconsumption: Implement measures to reduce excessive buying, such as school awareness campaigns and educational programs. Consider approaches like "choice editing" used in other industries (e.g., tobacco or cars) to guide consumer choices.

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- Consumer Protection: Enforce consumer protection laws to safeguard consumers from misleading advertisements and potentially regulate or restrict advertising practices.
- Promoting Repair and Reuse: Encourage repairing and reusing clothing, as it reduces the need for new garments and creates job opportunities. Government actions should repair and reuse economically viable.
- Addressing Overproduction: Tackle the issue of overproduction in the fashion industry, where a substantial portion of clothes goes unsold. Transition to zero-waste business models and establish criteria for businesses deserving of public support. Explore alternative exchange models to reduce waste.

These actions can help instill a sufficiency culture and mitigate the fashion industry's environmental impact while fostering more responsible consumer behavior.

4.2.2. Zero Waste strategies

Research into fashion sustainability (ElShishtawy, N., Sinha, P. & Bennell, J. A., 2022) asserts that the primary contributor to textile waste, especially in garment production, stems from the disconnection between the design and manufacturing processes. Designers conceive garment designs, while pattern makers create patterns for efficient fabric utilization, although this efficiency still needs improvement. Consequently, the design largely determines the waste generated during garment production.

Zero-waste fashion Design (ZWFD) has emerged to challenge industry norms and inefficiencies in the design-to-manufacture process. Zero-waste fashion Design Practices (ZWDP) are rooted in the concept that fabric and form are intricately linked. The central tenet of zero waste design is maximizing fabric width for either a single garment or multiple garments (McQuillan, 2020b). The term "zero waste" was initially introduced in the fashion context by Fletcher (2008) to revolutionize the entire fashion system and supply chain, encompassing everyone from farmers to consumers, all while embracing the principles of the circular economy.

It is worth noting that zero-waste design is not a novel concept; it existed in various cultures long before the industrial age. Zero-waste clothing can entail eliminating cuts in the fabric or wrapping the fabric length around the body, as seen in the Indian sari. Alternatively, it can be based on minimal cuts, as demonstrated by the Japanese kimono, which relies on folding, draping, and geometric cuts in garment construction. Distinct valuations of fabric drove these techniques.

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4.2.3. Zero Waste from the perspective of the fashion design practice

According to McQuillan (McQuillan, 2020), traditional garment construction methods have prioritized simplifying stitching to reduce labor costs, often disregarding broader environmental impacts. Contemporary pattern cutting, especially for cut-and-assemble garments, involves translating 3D garment designs into 2D patterns by flattening seams, gathers, and darts. These methods originated in a small-scale cottage industry context and need to adapt to address the current environmental crisis.

Zero waste fashion design, in particular, emphasizes the interrelationship between textiles and form, considering fabric width as a critical design parameter. To address environmental concerns, designers must develop holistic relationships with textiles that respect their materiality beyond their behavior and aesthetics (McQuillan, 2020).

In the last few years, several projects have emerged that tackle the environmental concerns of the textile and fashion industry from a creative and design perspective. From the literature review process, we highlight the following projects:

- **The Make/Use project** delves into "User Modifiable Zero Waste Fashion." (McQuillan, H., Archer-Martin, J., Menzies, G, Bailey, J., Kane, k., Fox Derwin, E., 2020). The project presents a built-in navigation system within garments that assists users in understanding the garment's structure and how it can be customized. Make/Use project uses textile prints and a parametric matrix to help people transition from flat 2D designs to 3D clothing forms more efficiently. They are exploring how embedding clues and markers in the clothing can make it simpler for users to create and modify their garments, aiming to foster emotional connections and prolong the clothing's usefulness by including options for altering and visibly repairing it.
- **Digital 3D design as a tool for augmenting zero-waste fashion design practice** (McQuillan, 2018). This project introduces 3D software for zero-waste fashion design, drawing from the authors' industry and education experiences. It highlights the software's potential in visualizing and marketing garments, emphasizing its role as a versatile design and prototyping tool. The study employs an experimental approach, examining how the authors' design process transformed when integrating 3D software, offering insights into its usefulness for both 2D and 3D design aspects. The work done by McQuillan et al. showcases various examples of 3D software applications, demonstrating its ability to enhance the relationship between garment form, pattern cutting, and waste reduction. According to the authors, 3D software holds significant promise in advancing zero-waste fashion design.

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4.2.4. Concluding remarks

There is a pressing need for a significant change in the fashion and textile industry because it harms our planet in many ways. Rules have to change, governments should offer financial incentives for eco-friendly practices, and the fashion ecosystem should move away from the idea that buying more and producing large quantities is good.

The fast fashion industry has grown significantly in the past 20 years because it used cheap, synthetic materials and moved production to places with weak labor and environmental rules. This fact made clothes cheap, and people bought more in rich countries. To make a real change, companies should consider ensuring the actual environmental costs are included in the price of fast fashion. However, we operate in a new policy area that needs to be fully tested. More research is needed to determine what works best to reduce overproduction and consumption of clothing. Governments at all levels should be willing to try different options and best practices to align the textile industry with what our planet can handle.

5. Transition to a more circular economy: the strategic role of bio-based fibers in the textile and fashion industry

As illustrated above, several factors and strategies contribute to the transition to a circular economy, including the choice of fibers and materials used in the various stages of the textile and fashion supply chain.

The evolution of fibers is intertwined with the history of human civilization, local materials, and technologies. It has started with natural and local fibers from plants or animals. Its cultivation and consumption opened the door to the industrial revolution and mechanization. Then, naturally sourced materials were replaced by more affordable versions, such as synthetic fibers. Besides mass production, mechanized textile production has been consuming water and energy to speed up the fabrication process. Nowadays, the need to use bio-based fibers comes back to solve environmental concerns. Sustainable and recycled fibers are becoming prominent alongside synthetic fibers to push the boundaries of science, technology, and local production.

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5.1. Bio-based Fibers

In recent years, to reduce the impact that the textile industry is having on the environment and climate, the search for more sustainable alternative fibers has become a significant trend. Garment production contributes about 80 % of the total impact of climate change, mainly through the use of fossil fuels in production processes. Of this percentage, fiber production accounts for 16% of the climate change impacts. As a result, the current trend is to break the dependence on fossil fuels by replacing synthetic fibers with alternative fibers that are more sustainable and not derived from fossil fuels.

5.1.1. Why bio-based fibers

Bio-based fibers include a broad and diverse range of fibers of nonfossil origin, all derived from natural inputs, such as sugars, cellulose, or proteins (European Environmental Agency, 2022).

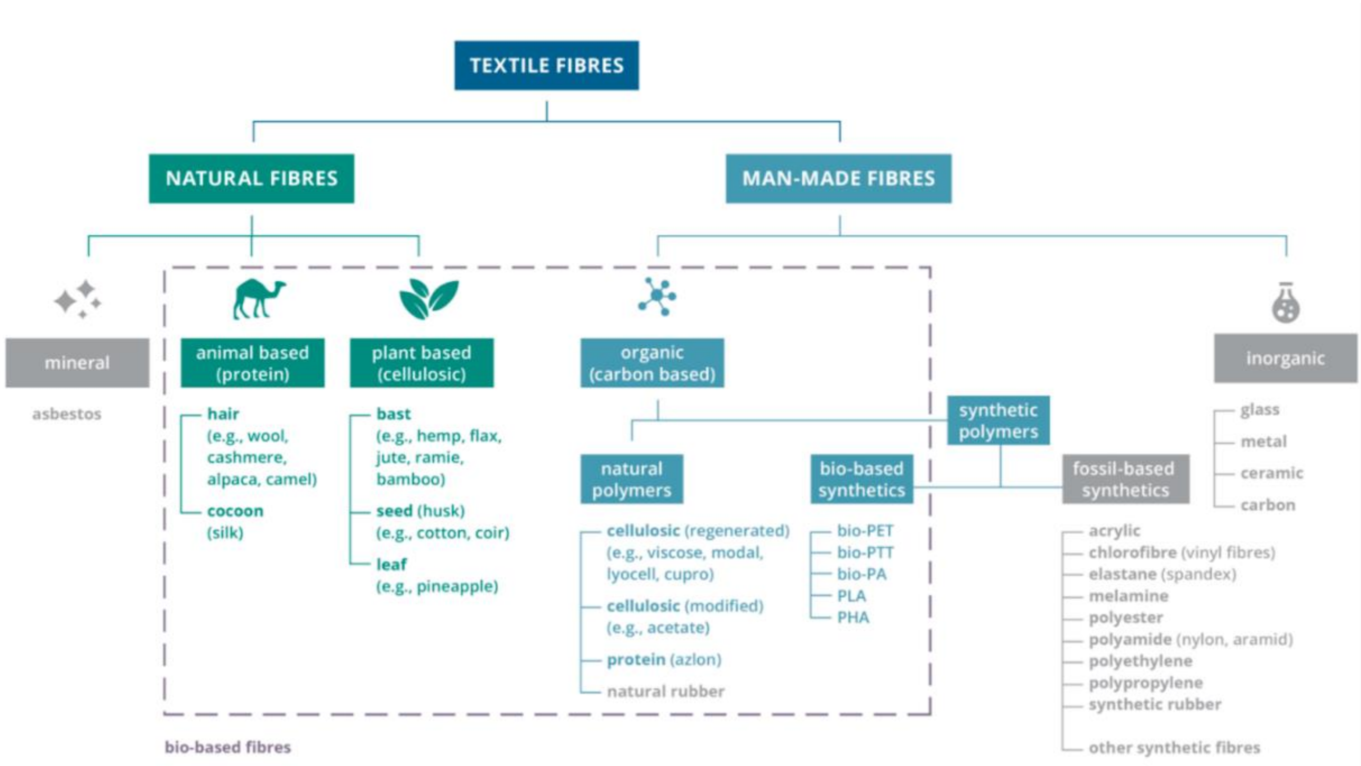

Figure 7. Current bio-based fiber types and their taxonomy. Source: Deckers, J. et al. (2023)

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Bio-based fibers can be divided between natural fibers and man-made fibers.

Natural Fibers: these fibers are made from natural resources and can be animal or plant fibers. Natural fibers can be divided between animal and plant fibers (Deckers J. et al. (2023).

The paper "The Role of Bio-based Textile Fibers in a Circular and Sustainable Textiles System" (Deckers, J. et al., 2023) summarizes the characteristics and applications of the main natural fibers.

Fiber	**Carbon backbone**	**Examples of favourable characteristics**	**Examples of unfavourable characteristics**	**Applications**
Cotton	Seed	breathable moisture absorbency strong soft, comfort	photoyellowing photodegradation prone to creasing slow drying susceptible to mildew	apparel baby clothing home textiles furnishing
Jute	Bast	strong low cost sound and heat insulating dimensional stability	coarseness stiffness harsh feel high fiber shedding photoyellowing creasing low extensibility poor washability	packaging furnishing upholstery carpets home textiles geotextiles automobile textiles
Coir	Seed husk	microbial resistance sound and heat insulating high elongation	short fiber length low stretchability thickness low tenacity at break	sacking floor coverings mattresses geotextiles automobile seats sofas
Hemp	Bast	moisture absorbency hypoallergenic heat regulation UV protection microbial resistance resistant to deformation breathable	stiffness thickness heterogeneity low elongation	apparel (socks (antibacterial), denim, etc.) ropes canvas sails
Flax	Bast	strong	low elongation	casual wear

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		breathable moisture absorbency durability lustre smooth , soft1 resistant to deformation heat regulation	low stretchability heterogeneity (colour, strength) rigidness	luxury wear summer wear belts straps cords threads
Ramie	Bast	strong lightweight breathable long fiber moisture absorbency resistant to shrinkage quick drying	very low elasticity low abrasion resistance stiffness brittleness	apparel (suits, shirts, dresses, etc.) home textiles twines threads fishing nets
Wool	Hair	breathable moisture absorbing flame retardant good insulation heat regulating absorbs odours	low abrasion resistance moth infestation	apparel (suits, sweaters, winterwear protective apparel, sportswear, etc.) home textiles medical textiles
Silk	Cocoon	strong comfort (soft feel) heat regulating durability drapability lustre	photoyellowing and degradation water damage insect infestation microbial infestation high cost static	apparel (luxury wear, fine garments, wedding gowns, etc.) home textiles medical textiles

Figure 8. Overview of examples of characteristics and applications of the main natural fibers.
Source: Deckers, J. et al.(2023)

Man-made bio-based fibers: Most man-made fibers used in textiles are organic and made of carbon-based polymers. These carbon-based polymers can be chemically synthesized or be derived from natural polymers. Man-made bio-based fibers can be divided between natural polymers (regenerated or man-made cellulosic fibers) and e bio-based synthetics, fibers produced from sugars and starch by chemical synthesis processes (European Environmental Agency, 2022).

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Biobased fibers are gaining popularity due to their sustainability and reduced environmental impact, especially in the fashion and textile industry, where concerns about environmental sustainability and ethical sourcing are increasing rapidly.

It is known that fossil fuels are non-renewable finite resources that release carbon into the atmosphere, accelerating climate change, and understanding is growing on how great a part synthetic fiber use plays in this (European Environment Agency, 2021). The inextricable links between overproduction and consumption, fossil fuel-derived products and services, depleted land that no longer produces high-value raw material, and the worsening climate crisis mean that brands, organizations, service providers, manufacturers, legislators and governments are (beginning to) recognize the need to divest from the use of virgin non-renewable resources and approach manufacture, use and reuse through low-impact circular models – including raw material alternatives.

Key examples of these important roadmap legislations are the EU Strategy for Sustainable and Circular Textiles and the EU Biodiversity Strategy for 2030, both of which contribute to the objectives of the European Green Deal. Together, these have an impact on the future of natural fiber production and use in the EU, with a focus on a holistic understanding of the interdependence of soil health (European Commission, 2020), fiber origins, garment use, longevity, and end-of-life solutions for manufacturers and users.

The EU textile ecosystem has been deeply affected by the COVID-19 pandemic, which, in combination with ongoing extreme weather conditions affecting fiber crop yields worldwide (Tariq Muhammad and Khan, 2022), highlighted a significant vulnerability in our supply chains and a reliance on imported energy and raw material supply to produce goods.

Therefore, there is a rising voice amongst Circular Economy advocates, such as the Ellen MacArthur Foundation, and natural fiber advocates with a focus on fashion and textiles, namely Textile Exchange, Fibershed, Material Alliance, and Woolmark, calling for research, diversification, promotion and investment into local fiber use, crop cultivation and processing. In shorthand, Fibershed NL (an affiliate of the international organization Fibershed, which is composed of bio-regional textile-fiber producing representative groups) uses their tagline 'Use what we have and use what we grow' to introduce the concept of bio-regional fibersheds, which focus on holistically managed hyper-local (native or climate-appropriate) textile fiber production and use (Jaspers and Nieuwenhuis, n.d.). This style and scale of the textile industry are mirrored in the report undertaken for the EU commission titled 'Durable, repairable and mainstream: How eco-design can make our textiles circular', which states a main objective should be to: "Promote sustainably and ethically sourced materials, provided it goes hand-in-hand with overall reduction of virgin resource use and the introduction of an ambitious mandatory due diligence legislation that ensures the full lifecycle of textiles is covered."(Botta and Cabral, 2021)

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The introduction of Extended Producer Responsibility to legislation will also signal a change in synthetic fiber usage as we work to decouple textile waste generation from the growth of the fashion sector.

5.1.2. Ecological aspects

Soil quality is essential for the successful cultivation of bio-based fiber crops. Over time, improper land management practices, such as excessive use of synthetic fertilizers, can degrade soil health as they require a considerable amount of water consumption during the growth stage and production processes. Animal production and the food supply chain can have a significant impact on soil quality, causing a consumer's unfulfillable demand at the same time.

Unlike natural fibers, synthetic fibers are primarily characterized by the fact that they are not biodegradable. As much as they are lightweight and physically appealing, true behind their visuals are the chemicals that are often used to color them. These pleasant colors are, however, harmful to the environment. Another reason is their long lifespan, which usually ends up as landfill.

5.1.3. Research approach and innovation

Biobased fibers come from organic materials; however, the need to achieve similar properties to synthetic fibers is high. The research approach of textiles is shifting from the outdoor fields into the laboratories, creating new job opportunities in the field of fashion and requiring new methodologies from the educational perspective.

In addition, new educational programs such as Material Futures, Biodesign Master, or Fabricademy - Textile and Technology Academy are trying to rethink teaching methodology focused on problematic issues of design, industry, and hands-on practice. With applied teaching and theory simultaneously, they try to prepare new researchers with different backgrounds for a long battle with the challenges of the fashion industry, energy, or food system. They emphasize every part of the research processes, from defining the topic, creating context, proposing solutions, defining its lifespan, and ensuring sustainability to recycling options.

5.1.4. Application, usage and industry

After approaching a final project, a petri dish or any prototype in an early research stage might have been turned into a business. The research area of bio-based fibers has been focused on the replacement of synthetic fibers and animal-based materials such as silk, leather, or fur. As much

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from the aesthetical part as from the durability and ethical aspects of the materials. Plant, fungal, or microbial materials are turning into vegan replacements, becoming an optimal alternative for many brands dealing with sustainability. Production is less costly and more environmentally friendly than any traditional leather or silk manufacturing (Kamm M., 2022). It can reduce and optimize consumed energy and ecological impact on the environment, compared to the traditional silk producers.

One of the protein fibers that is pointing questions regarding silk production is AMSilk or Spiber INC, which produces protein-based fibers through fermentation with sugars and microbes. This material has been used in sportswear or footwear for its high-performance and polyester replacement. On the other hand, there is silk-like cellulose-based material from the Orange fiber as a plant-based silk replacement. It comes from the orange peel leftovers with a lower carbon footprint. Together with Salvatore Ferragamo and H&M, they launched a serial pret-a-porter collection, which was also awarded the H&M Foundation's Global Change Award in 2015. Their annual open call has been looking for young innovators to accelerate their research projects, turn their ideas into marketable products, scale up, and slowly change the impact of the textile industry.

The same support also comes from the Lenzing group, which focused on the intersection of the linear supply chains that end in textile waste to achieve circularity. It offers recycled fibers Tencel from wood pulp alongside nonwoven textiles for medical high-performance use with biodegradable qualities. The innovation center is trying to come together with the industry to develop a material with enough quality to meet industrial use that would make it easier to redesign its life cycle and expand recycling options.

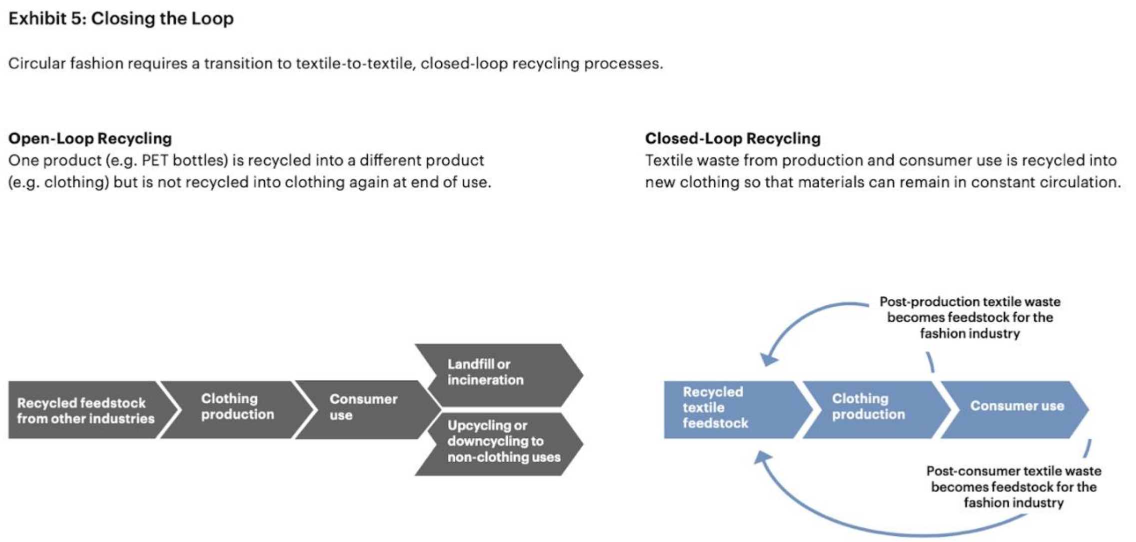

Figure 9. Closing the Loop. Source: Deeley, R. (2022)

5.2. The role of natural fibers in the green transition

As previously introduced, natural fibers – animal and plant-based- are part of the bio-based fibers. Animal-based natural fibers include animal hair (e.g., wool, cashmere, camel) and cocoon (silk). In contrast, plant-based fibers include seed (e.g., cotton), bast (e.g., hemp, jute, flax, ramie), and leaf (e.g., pineapple) (International Fiber Journal, 2023).

Natural fibers represent a large part of the future of textiles and materials for Industry 4.0. However, currently, the world's most used fibers in fashion and textiles are synthetics, such as polyester and polyamide, followed significantly by cotton.

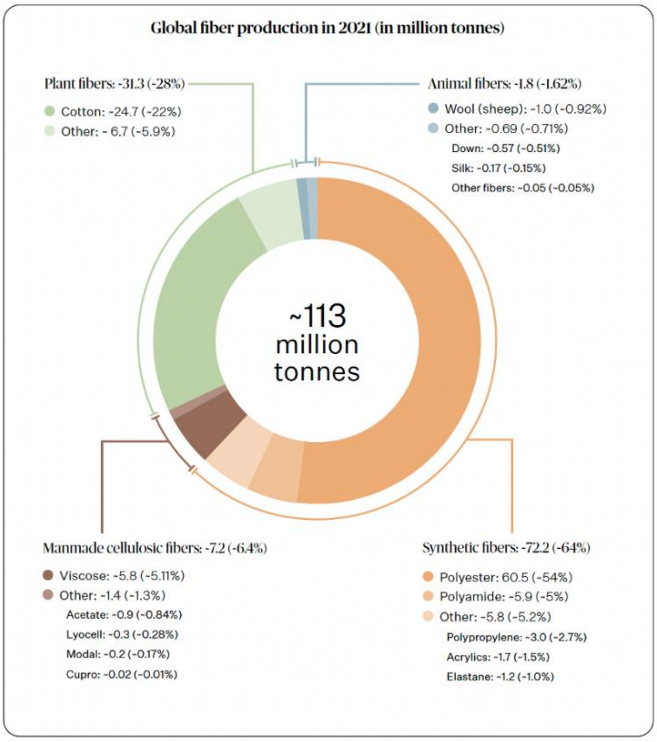

Figure 10. Source: Textile Exchange - Screenshot from 'The Global Fiber Market 2021, p.10, Preferred fiber and materials market report, October 2022, Accessed 24th August 2023

Such predominance of synthetic fibers, however, was only sometimes the case, as can be seen in the diagram below, which depicts a predicted roadmap for global fiber usage by 2030. Since the 1970s, production and use of synthetics have steadily risen. From the early 2000s onwards, synthetics such as polyester and polyamide have overtaken cotton and dominated the global fiber market, with only projected growth. While this shift has happened over time, it is only in the last 23 years that this reliance on synthetics has been cemented. Comparatively, cotton production and use have grown steadily, in line with increased production, throughout this period.

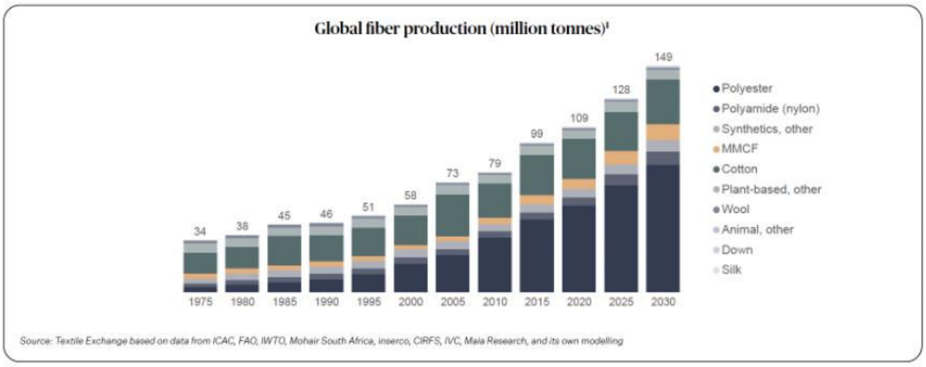

Figure 11. Source: Textile Exchange - Screenshot from 'The Global Fiber Market trends', p.9, Preferred fiber and materials market report, October 2022, Accessed 24th August 2023

This drastic proliferation of synthetics can be attributed to the fact that "global textiles production almost doubled between 2000 and 2015, and the consumption of clothing and footwear is expected to increase by 63% by 2030, from 62 million tonnes now to 102 million tonnes in 2030[6]"(European Commission, 2022). Driven by low cost, fast production times, and an ever-increasing demand for fast fashion, synthetics (with their industry-standard reliable production methods, independent of weather and crop yields) have allowed the cost of production and consumption to be radically reduced, giving consumers what they want, when they want it – but at what cost?

5.2.1. The role of Natural fibers in eco-design

As previously introduced, eco-design could play a critical role in reducing the impact of textile and fashion on the environment and producing textile waste. Natural fiber use can aid the goal of "design for low impact". Many natural fibers have international fiber-specific managing bodies such

[6] *The global fiber production data sets differ between the Textile Exchange (US) and the EU Strategy.

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as the Better Cotton Initiative, OEKO-TEX, Woolmark, and the European Alliance for Flax-Linen and Hemp. There are affiliated sustainability certifications, such as Global Organic Textile Standard, Regenerative Organic Certified, Fairtrade Certified, Responsible Wool Standard, and Fibershed's own Climate Beneficial Fiber certification. These organizations and certifications, not all named here, separately ensure supply chain transparency in various ways: by measuring climate impact through variables such as Greenhouse gas emissions, water usage, and pesticide usage; by monitoring fiber popularity quality standards, and by regulating cultivation and harvesting practices, including control of harmful substances and animal treatment, and ensuring labor rights such as fair pay, safety and treatment of the workers who harvest and process fibers, and by upholding circular standards and fair trade. (FashionUnited, n.d.)

By using highly regulated and traceable fibers of natural origin, designers can better control the ecological and social impact of their designs. They can make informed decisions about which fiber is best suited for the item they design in terms of intended use and longevity, whether it has been produced according to good health and safety standards, and better understand its origin, its availability, how far it must travel to be processed and used in a garment. For example, if possible, by opting to use an organic, socially, and environmentally sustainably managed fiber (sometimes known as a preferred fiber (Textile Exchange, 2022d) that grows close to their manufacturing region, designers can theoretically reduce the impact of a specific garment in a few ways. In general, choosing local natural organic fibers indicates a potential reduction in energy use and pollution (such as microfiber water pollution and pesticide run-off) for the growing and processing of the fiber and a potential reduction in greenhouse gas emissions via a reduction in shipping and transport of raw materials, as compared to an imported synthetic fiber manufactured elsewhere. These fiber choices can also improve or build local industry by providing jobs for local communities (Townsend, 2023)and improving supply chain resilience (Deeley, 2022).

Designers can also go beyond natural fiber usage as a means of pollution and GHG emission reduction. Research shows that natural fiber crops and regeneratively grazing sheep are essential for biodiversity, soil health, and carbon sequestration (International Wool Textile Organisation, 2020). Regenerative agriculture, which draws upon indigenous restorative fiber-growing practices, is essential to the future health of our planet and raw material supply chains, as this set of practices looks holistically at the global fight against climate change: exploring it as an intersectional issue that is deeply linked with environmental and human systems. Regenerative approaches to fiber cultivation, such as crop rotation, companion planting, no tilling, and cover cropping, build and restore soil health through storing carbon. "The benefits of soil restoration can include improved fertility, reduced fertilizer and irrigation use, and greater resilience to stressors such as drought"(Textile Exchange, 2022). If designers understand this process, they may implement the use

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of these fibers and encourage brands to invest in regenerative organic agriculture programs, such as Patagonia, the Kering Group, and Burberry are already undertaking.

A departure from synthetic fiber usage is further urged due to the documented and growing body of research on microplastic pollution. Synthetic fibers are known for the unintentional release of microfibers into waterways, which ultimately end up in the food and bodies of many species, including humans. "As the highest amount of microplastics is released in the first 5 to 10 washes, fast fashion, which is associated with the growing use of fossil-based synthetic fibers, has a high impact on microplastic pollution" (European Commission, 2022). As stated in the EU Strategy for Sustainable Fashion and Textiles, we must work towards a common goal that 'fast fashion' will be out of fashion by 2030. With consumer education, we can move away from hyper-short trend cycles and poorly manufactured items made in inadequate working conditions from synthetic fibers that shed plastic pollutants, hopefully towards a market with a more profound respect and understanding of natural fibers and man-made cellulosic. Designers and manufacturers can also influence this by producing garments of mono-material natural fiber origin.

Eliminating fiber blends from textile and garment design can have multiple benefits. Mono-material garments made from fibers such as regenerative organic cotton, hemp, wool, or European linen can be examples of long-lasting, timeless garments. While they will represent a greater investment for both producer and user, these garments generally have a perceived higher long-term value, as the fabric quality itself remains better after multiple washes and wears, with specific approaches to their care and maintenance. The greater perceived 'raw material' value of garments such as these also promotes the EU goal of longevity for garments, as it encourages both reuse through formal and informal methods (such as hand-me-downs and re-commerce) and repair practices. In addition, mono-material design provides the highest possible chance of end-of-life recycling through either the mechanical or biological cycle.

While technologies are advancing to separate blended fibers, they still need to be in their infancy, not at scale, and represent further higher levels of resource use to break the blends at the molecular level (Egan et al., 2023). Natural fibers can be recycled by mechanical or chemical processing or can be kept in the biological cycle whereby they are composted, thus returning nutrients and stored carbon to the soil, as can be seen in the diagram below.

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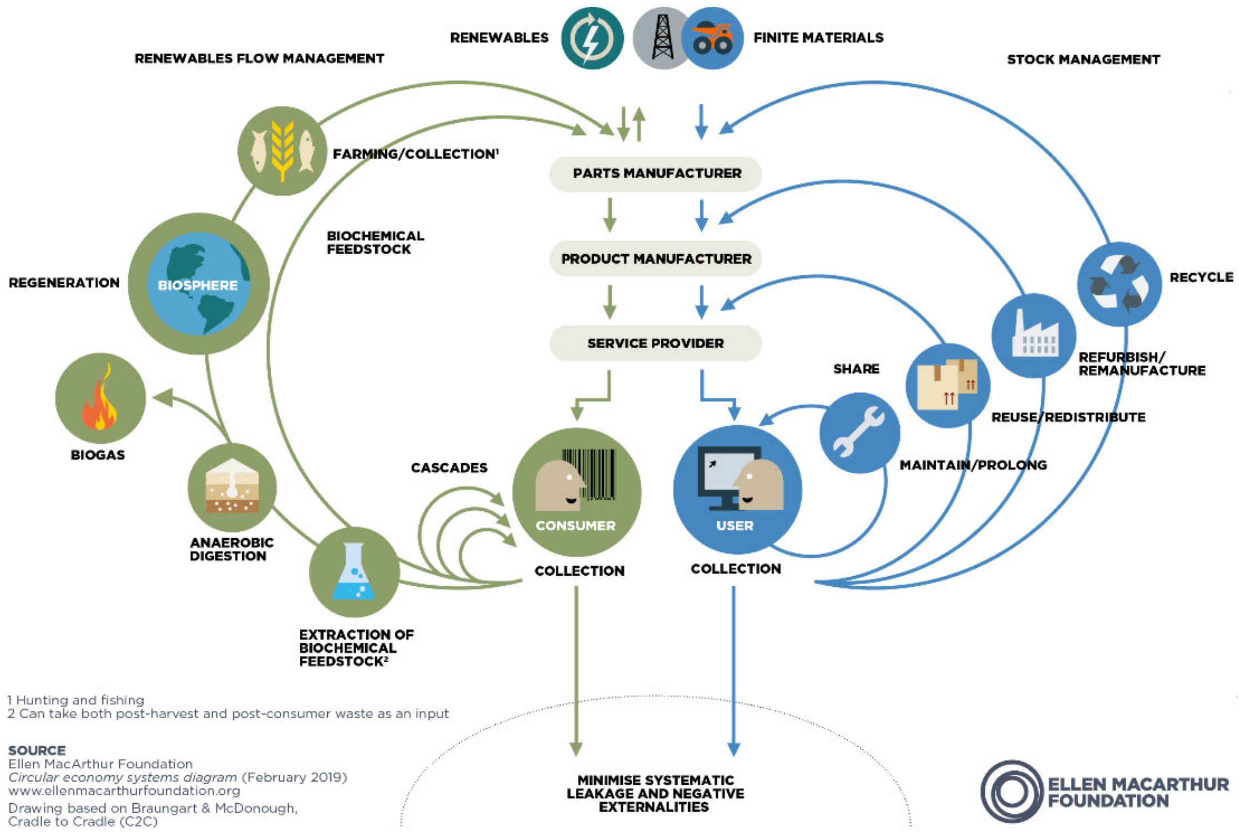

Figure 12 – The Butterfly diagram: visualising the circual economy Source: Ellen MacArthur Foundation, n.d.

Scaling back the production of blended fabrics will mean a potential loss of comfort that consumers have come to expect, such as elastane in denim jeans, and a potential increase in 'worn', crumpled-looking clothing, e.g., by removing polyester from polycotton blended garments.

It will also demand higher selling points for garments, which can be seen as exclusionary. However, it is believed that through user education and targeted sustainability communication, such as that outlined in the Sustainable Fashion Communication Playbook (UN environment program and Fashion for Climate, 2023), brands and advocacy organizations can shift the expectations people have of their clothes, making planetary health a priority, above all else. After all, there will be no fashion on a dead planet (Extinction Rebellion UK, 2020).

Based on all the information above, a move to greater use of natural fibers seems urgent and possible. The following paragraphs indicate the most common natural fibers likely to be seen in higher use in the EU for the green and digital transition. The following will focus on organic and regenerative fiber cultivation and the specific fibers of cotton, flax, hemp, and wool. We have chosen to exclude luxury fibers and materials such as silk and cashmere because the growing and processing of these materials exclusively happens outside of the EU, make up a tiny portion of global preferred fibers and materials, and are regularly under scrutiny for their necessity, considering the involvement and welfare of animals in this process.

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5.2.2. Cotton: Organic, Regenerative and Recycled

Cotton is currently, and will likely continue to be, the dominant global natural fiber, making up 24% of global fiber production. Such fact is because of its long-term mass cultivation and physical property benefits: it is strong, breathable, natural, and renewable, and is grown and processed in around 70 countries. However, 'conventional' cotton is known to have its problems. It relies on a vast amount of water to grow and can be chemically intensive. The enormous yields of cotton required to supply global demand require heavy use of pesticides, which contaminate soil, ground, and surface water and can harm people who harvest and process it. In addition, the synthetic fertilizers required for good quality cotton also result in water contamination and greenhouse gas emissions, and there are ongoing concerns about forced labor and conventional cotton production (Textile Exchange, 2022c)

Recognizing its market dominance and stronghold in the ecosystem of textile production, Textile Exchange leads research and initiatives into transforming the cotton industry into a baseline Organic industry, intending to encourage holistic regenerative practices further - once organic cultivation is reached. Brands are encouraged to work directly with cotton farmers to build resilient and fixed supplier relationships. They can do this by investing in 'in-conversion' cotton, which is currently transitioning to being grown organically. When not possible, sourcing organic cotton through cotton initiatives such as the Better Cotton Initiative, Raddis Cotton and Fairtrade Organic supports ongoing research into developing sustainable and regenerative practices, and ensures good labour rights and fair pay across the supply chain. (Textile Exchange, 2022a)

Whilst cotton will remain a significant player in the global market, it is important to recognise that Cotton is a non-EU-local fiber and is mostly unsuitable for cultivation in the EU climate, apart from Spain and Portugal where it is grown in very small quantities (Textile Exchange, 2022c). Therefore, a continued reliance on imported cotton – whether organic, regenerative, or recycled, has attached GHG shipping emissions and indicates a point of weakness in the textile supply chain. Cotton will also fare the worst as global temperatures increase as predicted, due to a likely shorter growth period of the fiber-producing boll, resulting in both smaller yields and fewer high-quality long fibers (Tariq Muhammad and Khan, 2022).

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5.2.3. Bast fibers: Flax, Hemp, Other

Flax

Bast fibers represent an alternative to Cotton, some of which readily grow in the European climate, such as Flax and Hemp. Flax is a plant that grows up to 60 cm tall and has slender but very fibrous stems. It takes 100 days to grow from germination to harvest. This food and fiber crop has been cultivated for millennia for different uses, including paper, oil, composites, and textile linen. Linen has high moisture absorption, is durable, comfortable, and cool against the skin, and in both historical and contemporary fashion, is considered a luxury fiber of high material value. Flax grows best in areas where the temperature remains below 30°C and has great success along the coastal strip of France, Netherlands, and Belgium (Deckers, Manshoven, and Mortensen, 2023). Flax requires little to no irrigation – requiring only about 700mm of rain annually. It requires few fertilizers and pesticides (compared to Cotton), and its initial stages of processing are completely biological as a result of natural dew retting in the fields in which it grows. It is further processing of stem breaking (scutching) and combing (hackling) are mechanical processes, whereby no chemicals are used, and all parts of the plant (seeds, stem shives, short and long fibers) can be used and valorized (Alliance for European Flax-Linen & Hemp, n.d.).

While flax is still grown in this European region, the opportunities for industrial processing and spinning of the fiber are limited, and harvests are often exported for processing to countries such as Poland. Initiatives such as The Linen Project, which was co-initiated by Artez University MA Practice held in Common and Crafts Council Nederland, are exploring Flax cultivation as a shared stewardship model (Textile Exchange, 2022b) that focuses on Commoning: a practice of collaborating and sharing to meet every day needs and achieve well-being of individuals, communities and lived environments. Growing smaller quantities of organic flax through traditional hand methods opens a dialogue in the Netherlands around re-invigorating local industry, knowledge sharing of ecological land management practices, and a commitment to ground-to-wardrobe craft-based fashion and textile practices. To scale this approach further, small-scale bast fiber processing mills would need to be re-instated in the region to reflect a local, networked, Fibershed-approach to this bio-regional fiber cultivation. (Fibershed, n.d.)

Hemp

Similarly, Hemp is a fiber plant that can grow under versatile weather conditions almost everywhere in Europe. France is currently the global leader in hemp fiber production by quantity.

It proliferates and needs little water to cultivate. It also has a deep root system, which helps to reduce soil loss and erosion and is useful in many different crop rotations. Therefore, it can be considered a regenerative crop when cultivated holistically. In addition, Hemp offers high moisture absorbency, is hypo-allergenic, and offers UV protection. While long hemp fibers are most desirable in terms of the

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favorable characteristics mentioned above, short hemp fibers obtained after decortication have a high 'colonization' potential, meaning they can be reduced to obtain soft and workable textile fibers that can be processed using existing cotton and wool systems.

However, hemp production and processing can involve relatively large quantities of fertilizer and machinery, both of which use a lot of water. Moreover, because Hemp is bulky, transportation to processing centers can be costly and energy-intensive. Therefore hemp production, as flax is described above, is only useful if done in combination with the investment in local, up-to-date networked fiber processing mills. Legislative barriers to the broader adoption of Hemp also exist. Hemp belongs to the cannabis family, meaning cultivation is under strict regulation, and little documented data exists about its cultivation. A positive side effect of the fact that Hemp has been prohibited in most nations for so long means that very few pesticides are permitted for its production – and very few are needed. However, in a recent study conducted by Textile Exchange, a concern was the comparatively high yield of Hemp cultivated in the Netherlands compared to crop size. Upon inspection, the Netherlands is the only country so far to approve over 81 pesticides for use on fiber Hemp crops. Such a thing is a dangerous indicator of how other European countries may give blanket approval of unnecessary pesticides in favor of high yields, disregarding the negative climate implications of this action – therefore, regulation is needed to ensure pesticide use is limited as much as possible.

Other natural fibers such as Ramie and Jute have also been known and used globally in ropemaking and fabric production for well over 6000 years. These fibers have similar properties to Flax/Linen and Hemp, hailing from plants native to China and South Asia, respectively. These are not suitable for cultivation in Europe under current climate conditions - and are not as favourable as Flax and Hemp, due to chemical treatment required for degumming Ramie fiber, and monsoon standing-water requirements for Jute fiber cultivation. A contemporary alternative to these fibers is Agraloop™ BioFiber™ an agricultural waste fiber produced by Circular Systems. Agraloop uses left-overs from various food and medicine crops including oilseed hemp/flax, CBD hemp, banana, and pineapple to create textile-grade fiber. Whilst still in its infancy, it proposes to achieve a 100% reduction in water consumption, compared to conventional cotton, 72% less fertiliser pollution than conventional linen and 52% less CO_2 than conventional hemp production, and therefore may be a good alternative.

5.2.4. Wool

Sheep wool is the most common animal fiber used in the fashion and textile industry. It's natural, renewable, biodegradable, breathable, resilient, and has good insulation and thermo-regulating properties. Sheep flocks have been managed for centuries across the world and thrive in variable

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climates. Sheep breeds can be indigenous to certain regions or imported, but are mostly bred and managed with a view to the suitability of the landscape and climate in which they graze. The Merino sheep is regarded as the highest value fiber producing sheep, due to its ultra fine long fleece. Merino sheep were once endemic to Spain, however in the 18th Century flocks were sent throughout Europe, and even as far as South Africa, Australia and New Zealand. The latter countries now have monopoly on the breed and are the largest producers of quality fiber, but Europe also has breeds that have been cross-bred with the Merino for dual benefits of high quality fiber and sheep hardiness. Italy remains a stronghold in wool fiber production and processing (International Wool Textile Organisation, 2020) As a result of the long history of wool production, and its lasting presence, wool garments are societally perceived as high value 'investment' items that stay in circulation for around 20-30 years, often having more than one owner – which is much longer than the average garment, which stays in our wardrobes for on average 7 years (ITWO in International Wool Textile Organisation, 2020).

Sheep graze pasture, digesting and absorbing atmospheric carbon that has been photosynthesized by the plants they eat. This carbon is then stored in the wool they produce, and is kept in the fiber as it is transformed into yarn or felt products. All wool can be used – when sheep are sheared, the fleece is graded; the highest micron counts are the finest fibers, which are used for spinning into fashion yarns for luxury garments, whilst coarser wools can be used for interior applications such as upholstery fabrics and rugs. Wool that does not make these grades can be used in insulation of buildings, and the dirtiest, short unusable wool can be composted, whereby the sequestered carbon returns to soil.

Unfortunately, in many EU countries, the demand for wool is less than supply, as wool is also a waste by-product of the meat industry. Industrial scaled farming methods have separated the 'whole' of the sheep and bred selectively to produce higher-value meat sheep for the food industry, resulting in lower quality fiber fleeces. There is little to no market for this wool as we have only a few places left for processing and

spinning – like with the other fibers mentioned, the textile industry moved predominantly to China, where production costs are lowered due to mass manufacture, and lower cost of labour. As shipping to wool is also a costly option, many fleeces in the EU end up being stored and burnt, therefore releasing the carbon stored in the fiber back into the atmosphere.

We know wool to be a super performance fiber that has multiple benefits for both wearers and the planet; wool reacts to changes in body temperature to keep the wearer warmer when it is cold and cooler when it is warm. It is also odour and wrinkle-resistant, which means that woollen clothing doesn't need to be washed as often as other fiber types do, saving water and energy.

Regenerative grazing, often used as a holistic land management practice in rural landscapes, sequesters carbon in wool fiber and increases biodiversity of pasture, allowing a natural cycle and livelihoods of contemporary shepherds to flourish. However, to see wool become the mainstay fiber it could be in the EU, investment is needed into expanding, networking, and decentralising the

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knowledge, equipment and processes used for wool production and recycling in the Prato region in order to make EU wool production a local, viable, low impact option.

As the wool industry looks promising for EU use of natural fibers, due to its local and historical low-impact, we must also be mindful of the practices used in animal husbandry, and their associated environmental implications. There is a risk of mismanagement and handling – such as distress, hunger, malnutrition, and mulesing, which makes sheep vulnerable to painful diseases (International Wool Textile Organisation, 2020) As with all other natural fibers, brands should seek to work with known certified farms and farmers. Examples of these include the Woolmark certification, and the Responsible Wool Standard from Textile Exchange, which '"recognizes the best practices of farmers; ensures that wool comes from farms with a progressive approach to managing their land, and from sheep that have been treated responsibly; Creates an industry benchmark that will drive improvements in animal care and land management and social welfare where needed; and provide a robust chain of custody system from farm to final product so that consumers are confident that the wool in the products they choose is truly RWS." (Textile Exchange, 2021)

5.2.5. Conclusion

Overall, the outlook for natural fiber usage in the future of textiles and materials for industry 4.0 and green transitions is positively high. Industrial developments, legislation changes and consumer education all point the way to an increased use of natural fibers in the EU for fashion and textile manufacture. This must be coupled with overall reduction of virgin resource use – and therefore an increase in recycling of textiles – which can be achieved through using high-quality mono-material natural fabrics, free of harsh chemicals and coatings, at the design stage, which later perform better in mechanical and chemical recycling or biological decomposition cycle.

Increases in natural fiber cultivation must be strictly monitored to ensure the best organic and regenerative practices are being used to ensure that soil health is built and greenhouse gas emissions are limited, and water pollution and soil pollution is eradicated. This will also require significant investment into EU/local processing facilities to ensure fiber can be processed close to its source, to prevent unnecessary emissions relating to transport of raw material.

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6. Technology and digital tools for textiles and fashion design sectors for an industry 4.0 transition

Industry 4.0 represents a concept of industrial structure that organizes production methods. This concept aims to create factories that adapt more closely to production needs and processes and allocate resources more efficiently. It is based on technologies and approaches like the Internet of Things (IoT), Cyberphysical Systems, Factory 4.0, Culture maker (Do-It-Yourself Culture).[5]

In the mapping developed by the TRANSITIONS project, the current state of the art of the technological factors presented in the following chapters has been investigated.

6.1. Digital prototyping and additive manufacturing

"Under the name of additive manufacturing (AM), reference is made to a whole set of technologies that are capable of making virtual solid models into reality by means of a process that consists of depositing successive layers of finite-thickness material from the bottom to the top" (Jimeno-Morenilla A. et al, 2021).

6.1.1. Situating the topic and content

Fashion and accessories designers are exploring 3D printing as a new medium to express creativity and a futuristic perspective on contemporary culture and identity through clothing. Additive manufacturing is one of the disruptive technologies that is revolutionizing not only the way we manufacture but also our aesthetics and design approaches. Complex geometries and intricate shapes that were impossible to achieve with traditional fabrication methods can nowadays be easily realized with 3D printing.

The possibilities and applications are endless, yet they are not oriented towards massively produced 3D printed garments but are preferred for the ability of personal fabrication, on-demand production, and personalization. 3D printing brings us closer to the digitization of design workflows, exemplified by the concept of "File To Factory" (FTF), where consumers are able to purchase digital files and utilize

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online printing services and local hubs to produce. Additionally, when combined with 3D scanning technology, garments can be tailored to an individual's exact measurements and style choices, turning clothes manufacturing into a personalized and accessible service. This shift is part of a larger transformation being driven by the fourth industrial revolution, the digitization of manufacturing, and the need for sustainable, environmentally responsible production.

6.1.2. Applications of 3D printing

What has been observed thus far are 3D-printed costume parts, luxury garments, bespoke accessories, performative footwear, and haberdashery. We also see its great potential in assistive technology and prosthetics, where personalization is required to tackle specific mobility challenges. In 2009, pioneer designer Iris Van Herpen started using high-end 3D printing technologies, and her avant-garde, iconic garments have been, for years, a source of imagination for young designers who get started with the technology. Since then, many young students have been getting visibility with inspiring collections. Danit Peleg, as a fashion student, presented a bespoke collection for her graduation show, manifesting the ability to print clothes at home using a low-cost printer. Israeli fashion designer graduate Ganit Goldstein combined traditional embroidery and direct-to-textile printing to create multi-color printed kimonos in collaboration with Stratasys.
Designers are also trying to reinvent the haberdashery of clothes and invent new systems of joining fabric by 3D printing zippers, buttons, snap buttons, and clipping mechanisms. These small parts are technical mechanical parts, and when designed for disassembly, they allow reuse, repair, remanufacture, and recycling, minimizing their environmental impacts. Fabricademy graduate Brigitte Kock and her venture Paraprint.io specialize in seamless, mono-material, modular 3D printed garments that have adjustable sizes and can be entirely recycled.

Figure 13. From left to right: Danit Peleg, “The birth of Venus” collection, 2017; Ganit Goldstein: “3D Wearable collection”, 2020; Brigitte Kock, “3D printed lingerie”, 2020.

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Since shoes are made of rubber materials, foams, and elastomers in traditional injection molding manufacturing, they are the most suitable products to embark on in the 3D printing industry. Besides, shoes are a perfect case for customization as they need to be ergonomic, and everyone has different needs. United Nude was the pioneer in presenting a collaboration between famous architectural offices and a 3D systems company for a collection of 3D-printed shoes in 2014. They only made limited editions, but the company still does all the 3D modeling and rapid prototyping with additive manufacturing and mass production with traditional methods. The newest online platforms, such as Zellerfeld, Fused Footwear, Hilos, and Koo, offer ready-to-wear 3D printed shoes that one can order online and have more accessible prices.
Designing footwear requires much knowledge of materials, ergonomy, and comfort. There are specialized 3D footwear design courses offered by Footwearology, both online and locally, that focus on the blend of 3D printing and 3D knitting.

6.1.3. On demand production, customization and personal fabrication

One of the core aspects of the fourth industrial revolution was to shift away from traditional mass production systems and to enable on-demand production. Additive manufacturing makes on-demand production more feasible through rapid and precise prototyping of bespoke things, radically changing how we design, produce, and consume.
The advantages of on-demand production are plenty: manufacturing becomes responsive to the customer needs, it decreases overproduction and minimizes the stock inventory, and it empowers consumers with the ability to customize and personalize their choices.
Additionally, the machinery is not specialized to solely one industry. However, it may serve various ones, quickly adapting to types, quantities, and products and not becoming obsolete with the next technological breakthrough. The term for adaptability to production is flexible manufacturing, permitting versatility and simplifying supply chains.

One of the first platforms for customized on-demand manufacturing in the fashion sector is Nervous System Design Studio. In this generative design studio, one can customize, visualize, choose the material, and order to print a variety of accessories such as necklaces, rings, cuffs, jewelry, and other products.

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The accessibility and agility of additive manufacturing empower individuals to get involved in the production process, becoming prosumers being empowered to design, produce, experiment, and use in their own right. As machinery evolves, the prototypes can be considered final products, and local fab labs, maker spaces, and hubs can run small-scale productions, decentralizing the industry, becoming more inclusive, and bringing manufacturing back to a local level. Moreover, there is not even an absolute need for expertise in 3D design since there are many online platforms where one can either download for free or pay for 3D models, such as Thingiverse, TurboSquid, or Cults3D.

3D printing services shapeways, i.materialise, sculpteo and local networks of hubs, such as Dfactory in Barcelona, are generating an ecosystem to encourage the promotion and development of Industry 4.0.

6.1.4. The designer - technician duo

The emergence of 3D printing in fashion brings different expertise together, promoting multidisciplinary collaborations. As fashion designers do not have the required technical skills to create the files for 3D printing, we see collaborations flourishing between a fashion designer who brings ideas and creativity through sketches, mood boards, and paper prototypes and a technician who can be an engineer, architect, industrial designer that has skills in 3D modeling and 3D printing. Companies like Stratasys or services like Shapeways have been keen on sponsoring 3D prints to showcase the applications of the technology in fashion.
In 2013, the pioneer brand Victoria's Secret collaborated with the architect Bradley Rothenberg and the 3D printing service Shapeways to create 3D-printed lingerie. The astonishing piece was made in laser-sintered polyamide, thus nylon, coated in Swarovski dust and crystals. In 2018 Julia Koerner collaborated with the costume designer Ruth E. Carter for the movie Black Panther to create a futuristic, visually intricate 3D-printed crown and shoulder piece worn by Queen Ramonda.
Similarly, Iris Van Herpen, a pioneer in adopting 3D printing technologies, partnered with artists such as Anthony Howe and architect Neri Oxmann and the Belgian printing company Materialise NV, for her hypnotic garments that have been worn by Lady Gaga, Björk, and Tilda Swindon.
New career paths are emerging due to the rapidly evolving digitalization and the fourth industrial revolution. Designers are making their profession and obtaining a combination of both traditional pattern-making skills and digital 3D skills that are at the convergence of architecture, product, and fashion design.

For experts who can bridge the gap between the two, the nexus of fashion and technology has created new opportunities. These new emerging professions are Virtual Fashion Designers, 3D garment technologists, Generative AI specialists, Fashion tech specialists, and algorithmic fashion

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designers who can flawlessly combine fashion and technology to help fashion firms stay on the cutting edge of technological developments in the market.

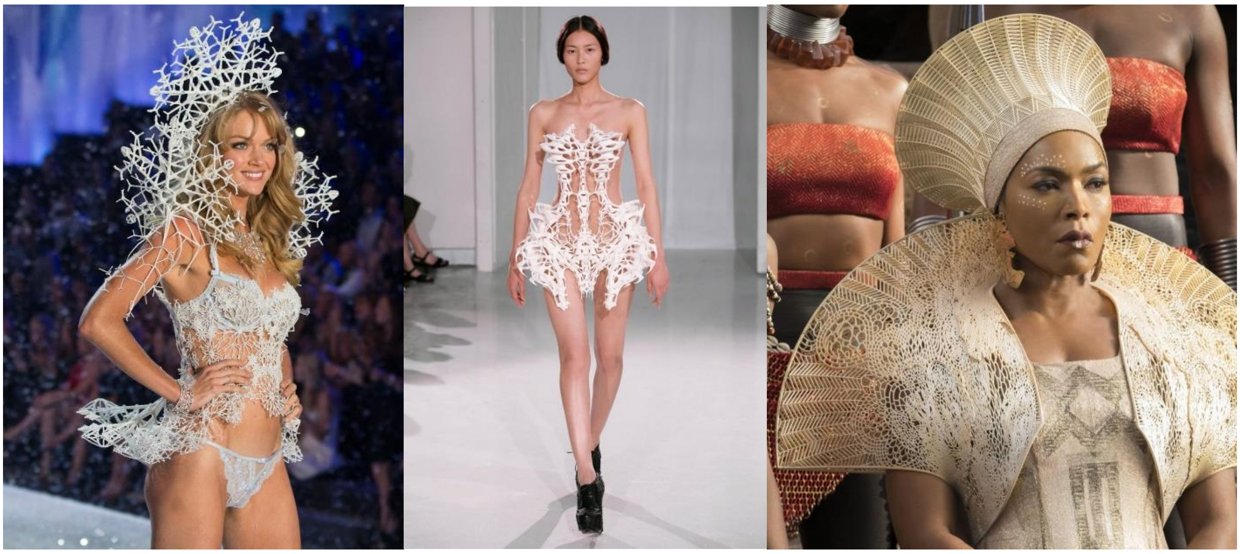

Figure 14. From left to right > 2013 Victoria's Secret 3D printed swarovski bra, 2017 Iris Van Herpen's Crystallization collection, 2018 Julia's Koerner Black Panther costume

6.1.5. Computational design tools

Digital manufacturing is paired with the knowledge of 3D modeling and computer-assisted design (CAD). This allows the designers to visualize and evaluate their creations beforehand, offering the creative freedom to explore innovative concepts without taking any risk in manufacturing. Computational design tools, in combination with easily accessible and cheap rapid prototyping, enable a constant dialogue between visualization and artifact, creating feedback loops where the designer can be informed by the fabricated objects, improve, and reiterate.

There is a broad offer of proprietary 3D modeling software that is not specialized in 3D fashion design. However, designers have shown a preference for Rhinoceros 3D with the Grasshopper plugin, which permits them to create complex, intricate forms using parametric design. Parametric design is based on algorithmic processes, where one does not directly design the geometries and shape but develops a system with parameters that generates infinite variations of elements, buildings, and products. It is a visual programming language that can generate simulations of materials, physics, and mathematical models and, most importantly, can use data to inform the design. For example, a model can be informed by the measurements of the body or by a 3D scan.

Blender is a free and open-source alternative for 3D modeling and 3D animation that also includes cloth simulations. It is a very powerful community-based project with many online tutorials for self-paced learning.

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Fashion applications of 3D design can either imitate fabric structures or be rigid like exoskeletons. For example, an armor-like chainmail composed of small interlaced pieces is the closest to the properties of a fabric. Prosthetics for custom solutions of assistive devices are mainly made of rigid materials.

Only recently and in very few courses have we found curricula of computational design software classes and 3D printing oriented to the textile and fashion sector. Some of those are the Computational Couture of Fabricademy, Textile and Technology Academy, Danit's Peleg online source, and Future Learn online introductory course on digital manufacturing and 3D printing.

6.1.6. 3D printing technologies and materials

Various additive manufacturing technologies can be used for fashion using various synthetic materials. The most efficient, cost-effective, and widely used in Universities, maker spaces, and homes is FDM-fused deposition modeling that functions via the deposition of melted filament in layers. There is a vast variety of thermoplastic polymers that can be used, both biodegradable and non-biodegradable.

For fashion applications, the most popular material is TPU, a rubber-like thermoplastic elastomer. Being elastic and soft, it resembles latex or EVA foam, and it can be malleable on the body or used for 3D-printed shoe soles. Rigid materials such as PLA, nylon, and ABS can also be used in sculptural pieces, accessories, and prosthetics.

A high-quality and precision 3D printing technology is SLS, selective laser sintering, which uses polymers in the form of powder and bed fusion sintering, permitting the production of complex geometries of pieces that would be impossible to produce with other fabrication methods.

SLS mainly uses polyamide powder, thus nylon.

The latest and most advanced is the Material Jetting technology (DOD-Drop on Demand), which uses photopolymer liquid resin that solidifies with UV light. There is a variety of liquid resins that can print in a full-color range and in multi-materials that can simulate everything, from hard plastics to human tissue. The resin cost is very high, approximately 400 euros per kilo.

3D printing on fabrics is a technique that has been experimented with for more than a decade in a hobbyist/maker environment by hacking FDM printers and adding a layer of fabric on the build platform. In May 2022, Stratasys, a leading 3D printing company further developing the technique, announced 3DFashion. This method enables direct-to-textile printing with a patent-pending semi-flexible material for robust adhesion on the fabrics using Polyjet, material jetting technology.

While the materials used for 3D-printed fashion bring new aesthetics and new ways of designing, they differ from the familiar soft natural materials like cotton, wool, or linen. The next significant

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pending innovations we will see in the sector will not be as much related to new 3D printing technologies. However, they will be in the materials innovation, both in the development of lighter, softer, and more “cloth-like” touch and more sustainable, biobased, and environmentally friendly solutions.

6.1.7. Sustainability and 3D printed fashion

The aspect of sustainability in 3D printed fashion can be challenging. Some obvious and very notable advantages promote sustainability in 3D printing. First and foremost, there is a radical reduction of waste and zero water consumption, which is crucial to fashion’s bad reputation. Moreover, it enables ultra personalization, pre-visualization, nearshoring, on-demand, and decentralized production, all aspects of the industrial and consumer needs of contemporary society.

High-end printers that print in multicolor and with a range of elasticities (multi-material) can fabricate a finished product, and, since the base material is the same, the whole piece can be entirely recycled with no need of disassembly is the pain point of the recycling process, since cannot be easily automated yet.

As mentioned above, there are various advantages in additive manufacturing, yet there are still many limitations and disadvantages.

In order to produce more sustainable garments and accessories, there are many steps in the process that should be taken into consideration. Starting with the design process, we can opt for zero-waste patterns, minimize waste, design for disassembly, use circular design principles, and choose the appropriate printing technology according to the geometry we wish to fabricate. FDM, SLA, and SLS technologies generate support material that needs to be post-processed, removed, and thrown away or recycled. On various occasions, the support material is more than the piece itself. On the other hand, they direct to textile and SLS technologies, print in powders, and have full support, so they can be considered wasteless.

The materials used for 3D printing are the majority of elastomers and plastics. In high-end printers, the cost of those photopolymers or powders is not affordable, and they are not eco-friendly. In FDM, the materials are recyclable and low cost, yet the resolution of the pieces is low. Using eco-materials, biodegradable or recycled materials can be beneficial, but more is needed to solve the problem.

Even though the materials are designed to last, the application of 3D-printed garments is for exceptional occasions. They are not designed for longevity and are worn just once. A potential solution to this problem could be to develop rental services.

We believe 3D printing will mature wisely towards more ethical, accessible, and sustainable manufacturing solutions as the fourth industrial revolution is further developed. The rapid technological advancements, the need for more sustainable practices, and regulations concerning

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the industrial environmental impact are already setting a proper framework of constraints to re-invent manufacturing within limits.

Core knowledge to acquire for additive manufacturing in the textile and clothing industry:

- Computational design tools
- 3D printing technologies
- Parametric design
- Advanced materials

Courses and pedagogical approaches

- ☑ Fabricademy Computational Couture
- ☑ Parametric House
- ☑ Hubs
- ☑ Rhinoceros 3D
- ☑ Online course with Danit Peleg

3D printing technologies

- ☑ FDM
- ☑ SLS
- ☑ Material Jetting
- ☑ Direct to textile

3D models Online

- ☑ Thingiverse
- ☑ Free 3D
- ☑ Sketchfab
- ☑ Turbosquid

3D printing services

- ☑ Shapeways
- ☑ I.materialise
- ☑ Wenext
- ☑ Hubs
- ☑ Materialise
- ☑ sculpteo

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6.2. Artificial Intelligence, Big Data and Automatisation

The fashion industry, historically rooted in craftsmanship and artistry, is undergoing a digital transformation. Two pivotal technologies driving this change are blockchain and big data. Their integration into the fashion ecosystem has profound implications for Industry 4.0 and sustainability. Integrating blockchain and big data in fashion signifies a move towards a more transparent, efficient, and sustainable industry. As blockchain and big data technologies become more prevalent within the fashion industry, Industry 4.0 principles become more pronounced, offering both challenges and opportunities for brands and consumers.

In the following, we give a short overview of the applications of these technologies in the fashion business and conclude with the consequences for Industry 4.0 and sustainability. After that, we give a short but by no means exhaustive overview of recent commercial and institutional initiatives in the field.

Blockchain in Fashion

- **Traceability and Authenticity**: Blockchain's decentralized ledger system offers unparalleled traceability. Brands can track the origin of materials, ensuring ethical sourcing and combating counterfeit products (Kshetri, 2018).

- **Transparent Supply Chains**: Blockchain provides transparency in supply chains, allowing consumers to verify the sustainability claims of brands (Saberi et al., 2019).

- **Secure Transactions**: Blockchain facilitates secure peer-to-peer transactions, reducing intermediaries and associated costs (Tapscott & Tapscott, 2016).

- **Digital passports**: provide detailed information about a product's lifecycle, from raw material sourcing to production and distribution. This transparency ensures ethical practices and promotes sustainability.
- Life cycle assessment: A method to evaluate the environmental impacts of a product throughout its life cycle. By understanding these impacts, fashion brands can make informed decisions to reduce their carbon footprint.

- **Big Data in Fashion**
- Predictive Analytics: Big data analytics enable brands to forecast trends, optimize inventory, and reduce waste (Wang et al., 2016).

- Personalized Experiences: By analyzing consumer data, brands can offer personalized shopping experiences, enhancing customer loyalty and reducing returns (Chen et al., 2018).
- **Efficient Supply Chain Management**: Big data can optimize supply chain operations, ensuring timely deliveries and reducing overproduction (Tiwari, S., Wee, H. M., & Daryanto, Y. 2018).

Implications for Sustainability and Industry 4.0

- **Automation and Interconnectivity**: Both blockchain and big data promote automation. Blockchain ensures secure data exchange, while big data analytics can automate decision-making processes (Lu, 2017).
- **Real-time Data Exchange and supply chain automation**: Industry 4.0 emphasizes real-time data exchange. Big data analytics provide real-time insights, and blockchain ensures the secure and transparent sharing of this data (Zhong et al., 2017).
- **Ethical Sourcing**: Blockchain's traceability ensures materials are ethically sourced, promoting fair labor practices and sustainable material sourcing (Köhler, 2020).
- **Waste Reduction**: Big data analytics can predict demand, reducing overproduction and associated waste (Ferasso et al., 2019).
- **Conscious Consumption**: Transparent supply chains allow consumers to make informed decisions, promoting conscious consumption and sustainable purchasing behaviors (Tse et al., 2020).

Existing Projects and Initiatives

- **TRICK Project**[7]: While specific details were not accessible, projects like TRICK often focus on integrating technology into the fashion industry to enhance sustainability and efficiency
- **Traçabilité 1**: The Chaire BALI, supported by ESTIA, focuses on the technological disruptions in the fashion and textile sector. One of its primary research areas is traceability, emphasizing circularity to provide meaningful offerings to consumers and enhance the value chain's flexibility. This approach aligns with the principles of Industry 4.0, emphasizing the importance of transparent and sustainable supply chains (chaire-bali.fr).
- **DAPHNE Project**[8]: Similarly, the DAPHNE project likely emphasizes the use of technology in fashion, although specific details were not available.
- **By Borre Create ™:** Fabric characteristics are digitalized using a digital textiles database that allows for a digital passport that has insights on impact, care and lifecycle to help the creator with more freedom in making a conscious choice.
- **Interfacer Project**: Projects like Interfacer aims to bridge the gap between technology and fashion, ensuring seamless integration and promoting sustainable practices.

[7] http://www.trick-project.eu
[8] www.daphneplus.eu

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- **GITLAB Fabricademy**[9]: A course that similarly focuses on educating individuals about the intersection of textiles, digital fabrication and biology, emphasizing innovative solutions of the industry 4.0.
- **Internet of Production**[10]: This alliance aims to reimagine manufacturing, promoting sustainable, globally networked, local manufacturing. They believe in decentralized manufacturing based on shared knowledge, emphasizing faster product delivery with less ecological impact.
- **Open Source Circular Fashion**[11]: Fabricademy's open-source initiative in fashion promotes collaboration, transparency, and sustainability. By sharing knowledge and resources, the industry can move towards a more circular model.
- **The Business of Fashion** (BOF) regularly publishes insights into the fashion industry's current state. Their reports likely touch upon the increasing integration of AI, Big Data, and Automation in fashion, emphasizing the implications for sustainability and the broader industry.

6.3. Augmented and virtual reality

The fashion industry's integration of Virtual Reality (VR) and Augmented Reality (AR) is reshaping consumer experiences and offering innovative solutions for sustainability challenges. These technologies, while enhancing user engagement, also play a pivotal role in promoting a circular economy and sustainable practices within the fashion sector (Birtwistle & Moore, 2007; Allwood et al., 2006). The integration of AR and VR in fashion aligns with the principles of Industry 4.0, emphasizing automation, real-time data, and interconnectivity. These technologies promote sustainability primarily by reducing waste associated with returns, promoting conscious consumption, and enabling brands to produce based on demand. That is possible as a result of a seamless and transparent remote collaboration between designers, suppliers, and retailers from across the globe who can collaborate in a virtual space, reducing the need for physical meetings and associated travel emissions (see Mackey et al. 2019 for a thorough overview) as with AR and VR, designers can have a more tactile and interactive experience with materials, even in a virtual environment, leading to more informed design decisions. At the same time, virtual platforms offer an avenue to merge traditional textile practices with modern design techniques. This fusion preserves not only cultural heritage but also introduces innovative design possibilities (Kuusk et al. 2013).

[9] http://www.gitlab.fabcloud.org/fabricademy
[10] www.internetofproduction.org
[11] www.oscircularfashion.com

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Following, we give an overview of the main current implications of these technological possibilities and the consequences for Industry 4.0 (and 5.0), together with some salient examples of commercial and research initiatives in the field.

Virtual Reality (VR) in Fashion

a. Virtual Fashion Shows: Brands have adopted VR for fashion shows, offering a global audience an immersive experience without the environmental footprint of traditional events (Perry, 2018).

b. Virtual Fitting Rooms: VR addresses online shopping challenges, reducing return rates and associated environmental impacts (Goldsworthy et al., 2019).

c. Design and Prototyping: VR aids in rapid prototyping, reducing material waste, and promoting sustainable design practices (Black, 2008).

Augmented Reality (AR) in Fashion

a. AR Try-Ons: Brands like Gucci have integrated AR for virtual try-ons, reducing the need for physical samples and associated waste (Realini, 2020).

b. In-Store Experiences: AR in retail stores can reduce overproduction by providing insights into consumer preferences (Kaplinsky & Morris, 2001).

c. Interactive Marketing Campaigns: AR campaigns can promote sustainable consumer behavior by offering insights into product origins and sustainability credentials (Joy et al., 2012).

Implications for a Circular, Sustainable Economy 4.0

The integration of VR and AR in fashion aligns with the principles of a circular economy by promoting longevity, reducing waste, and encouraging sustainable consumption (Webster, 2015). These technologies:

Reduce Overproduction: By understanding consumer preferences through VR/AR, brands can produce based on demand, reducing waste (Tukker, 2004).

Promote Conscious Consumption: AR can educate consumers about product sustainability, influencing eco-friendly purchasing decisions (Niinimäki, 2010).

Enhance Recycling and Upcycling: VR/AR can guide consumers on recycling or upcycling old garments, promoting a circular fashion lifecycle (Fletcher, 2008).

Many are the initiatives undertaken by large, existing brands and courageous entrepreneurs aimed at making these technologies work. In Europe, these are increasingly also driven by legislative changes. In the following, you can find a brief but by no means exhaustive overview.

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AR and VR in Practice

Gucci AR Filter: Gucci, a luxury fashion brand, introduced an AR filter allowing users to virtually try on its products, enhancing online shopping experiences.

H&M's 90s Collection Promotion: H&M leveraged AR by introducing six filters to promote its 90s collection, offering a nostalgic and interactive experience to its consumers.

Saks 5th Avenue: The brand introduced an App where shoppers could use smart glasses or phones to view virtual clothing in-store or at home. The App created a frictionless shopping experience, improving buyer confidence, increasing spending per visit, and reducing returned merchandise.

Ralph Lauren's Fifth Avenue Store: The flagship store in Manhattan introduced connected fitting rooms developed by Oak Labs. These rooms use RFID technology to recognize items and display available sizes, colors, and recommended products. The interactive fitting rooms have seen an engagement rate of 90 percent, emphasizing the blend of technology and human touch in enhancing the shopping experience.

The Fabrikant: it is a digital fashion house known for its innovative approach to merging technology with fashion.

Metaverse Fashion Week by Decentraland: it is a digital fashion week where brands, including The Fabricant, showcase new clothing collections in the metaverse. Unlike traditional fashion weeks, Metaverse Fashion Week was open to everyone, democratizing the fashion show experience.

6.4. Hands on into Textile Machinery: Open Source Hardware and Low-tech systems

Situating the topic and content

Textiles are part of daily use objects. We use them for clothing, warming, protecting, cleaning, and decorating; many textiles were developed with increasing technicity to respond to the population's needs and demands. Behind the diversification of textiles, complex processes, and machines were designed and installed worldwide, creating long supply chains from fiber to fabric to the product and vice-versa.

When transitioning towards more sustainable fashion practices, caring about the machines remains necessary. It is about being aware of what remains invisible, increasing our knowledge of fabrication machines, guaranteeing access to the required knowledge to fabricate or best use the tools, making sure they are fitting their purposes well, optimizing their eco-efficiency, limiting the harm its use can generate on people and environment.

Re-engineering tools to make textile machines and products accessible, sober in energy and material, and long-lasting requires a maker mindset with technical and problem-solving skills, an extensive system understanding, an appetite for innovation and DIY, and an engagement towards radical ecology and open-source practices. It also considers work situations as user experiences and being able to place machines in broader systems.

Core knowledge to acquire to get its hand into textile machinery for sustainable fashion transitions relies on the following:

- Fabrication technologies and production processes in the textile industry
- Open Source philosophy and practices
- Low-tech approaches and systems
- The art of making, hacking, and repairing
- Textile infrastructures for locally-productive cities

Machines in the textile industry: past, present and future

Current industrial sites, textile makers' studios, textile museums, library engineering and art schools, and archive books keep traces of textile machine knowledge at each process step, from extraction to production, distribution, maintenance, and recycling. Technological networks and databases are numerous but only sometimes visible to non-experts. We can mention the ITMA conferences that are held each year or databases like World Textile and Textile Technology Complete. Access to such processes might be restrictive or limited to educational or private institutions and with dedicated costs.

Appropriating technologies with open source hardware

Open-source hardware consists of physical artifacts of technology designed and offered by the open-design movement. It consists in making accessible the "code" of products, documenting how things are made, sharing the design files of products and list of components, procedures to assemble it. Both free and open-source software and open-source hardware are created by this open-source culture movement and apply a like concept to a variety of components, referred to as FOSH (free and open-source hardware). The community of Open Hardware met once a year in the Open Hardware Summit[12]. They exist upon reaction of opacity and lack of transparency in design and

[12] https://2023.oshwa.org/

production processes and industries, and for making accessible designs, letting the possibility for any designers and makers to learn and make how things are made.

Currently, few textile machines are present in hardware databases. The Fabricademy course entitled "Open Source Hardware- from fibers to fabrics[13]" gives a wide overview of existing practices. Libraries of student projects are also available with examples of redesigned and customized machines. The Hilo studio[14] works on open source machines for small-scale production from spinning machines to carding. Open source models for looms can be found easily on the web, mainly for manual and small size formats as the Indira looms[15] Jacquard machines are not documented yet. Small DIY machines for knitting, braiding are also accessible online via video tutorials. The Knitic project [16] consists of a circular knitting machine. The Little Wool Factory project[17] has listed and documented a series of machines available for processing wool. Taking part of the open source hardware communities comes with new skills to learn and processes to follow, where documentation has a strong role (see slide 66-67 of this presentation[18]).

There exist various types of licenses and standards for open source hardware projects (creative commons, GPL, OHL...). The open source hardware association[19] is compiling recommendations and examples on their website.

Business models and strategies differ according to the types of projects. Most of the time, services are offered to train and maintain the machines. Some companies build their model on an open-source hardware project that they improve and make proprietary. This is the case of the Kniterate machine[20] that benefitted from open design communities to then decide to adopt a more classic model of local suppliers with warranty for the product.

Low Tech systems: useful, accessible, low energy consumption and long-lasting

Over the past 30 years, large numbers of concepts and projects have been developed to better frame how to make more sustainable systems. Part of the debates occurred in questioning the role of techniques and technologies in the systems, highlighting the limits of the logic of accumulation, productivity, and efficiency, as well as the importance of sufficiency and accessibility. Authors such

[13] http://fabricademy.fabcloud.io/handbook/classes/07_open_source_hardware/
[14] https://www.studiohilo.com/
[15] https://class.textile-academy.org/2022/nanditha-nair/assignments/week10/
[16] https://hackaday.com/2013/03/26/giving-a-cnc-knitting-machine-a-new-brain/
[17] http://fabricademy.fabcloud.io/shemakes/handbook/2.-innovation-services/Lab-to-Lab-Research/
[18] https://docs.google.com/presentation/d/1w5CazC-hpjuTML7Nem20eEdVSp-lAEyxNrXtvOBYEG0/edit?usp=sharing
[19] https://www.oshwa.org/faq/
[20] https://www.kniterate.com/product/kniterate-the-digital-knitting-machine/

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as Illich (Illich & Lang, 1973), Ellul (Technique Ou L'enjeu Du Siecle, La Jacques Ellul: Economica: Free Download, Borrow, and Streaming : Internet Archive, n.d.), Schumacher(Ernst Friedrich Schumacher, 1973) has invited people to think on what could be more convivial technologies, and what technologies are needed for small-scale actions. The Degrowth movement (Kerschner et al., 2018) and, more recently, the Low-tech movement are creating new social imaginaries for the roles of technologies in our society. The Low-tech lab created a manifesto defining low-tech as objects, systems, techniques, services, know-how, practices, behaviors, and even ways of thinking that use technique and technology according to three principles: useful, accessible, and sustainable. The term "low" is opposite to "high" and is closely related to slowing the pace of current production systems and energy consumption. Databases of projects and research projects are now supporting the development of Low-techs (Abrassart, 2020; Abrassart et al., 2020; Tanguy et al., 2023).

The art of making, hacking, and repairing

Part of the knowledge acquired to make a more sustainable system is technical and hands-on and applied to objects relying on the skills of making, hacking, and repairing.

Designers have remarkable projects where they highlight the processes. Lara Campos, with its designs, shared the steps of the designs of the textile pieces poetically. Bridget Harvey and Laetitia Forst designed narratives around repairs and disassembly (Forst, 2020). Exhibitions, web portfolios, and social media accounts are all sources of inspiration. Platforms such Ifixit and fablabs.io are sharing good practices and tutorials that can be easily tested and applied in various situations. Training or community events such as design challenges and repair café can support people in increasing their capacities to make and repair. Finally, old books can serve as inspiration as the "Whole Earth Catalog" or "Con nuestros propios esfuerzos" group a list of tools and processes that support self-sufficiency and autonomous lives.

(Textile) infrastructures for locally productive cities

When reflecting on textile machinery, the territorial level brings new sights and challenges. It is not only thinking about the impacts of industrial sites but also about what is done, where, and by whom. In the textile sector, particularly in Europe, there is a current strategy for nearshoring, meaning relocating the production activities to where products are consumed. Essential projects can be mentioned, such as local and regional economic development used to work in clusters of companies where they list current activities and infrastructures. Current works on circular cities are looking at the metabolism of cities in terms of flows and resources. The project Textile (Life)Cycling from Amsterdam is a good practice of circular textile projects at the city scale. The movement of Fab City aimed at supporting cities in becoming locally productive and self-sufficient in 2054, is experimenting with new models (Diez Ladera et al., 2022; Ferro et al., 2022) with a bunch of more than 50 cities across the world, inviting their members to map their current craft and manufacturers ecosystems with the support of tools like Kumu or Make.works, to value the stories of making in their

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territories, to rethink what is the excellent scale of production, the balance between traditional and digital technologies, the socio-economic models that could foster prosumerism, fair practices and environmental challenges. In the Textile and Clothing sector, textile labs act as enablers of such vision, being places of training, research, and prototyping at the interface with local and global stakeholders participating in sustainable transitions. (Ferro et al., 2022; Marsh et al., 2022; Real et al., 2020, 2018)

6.4.1. Pedagogical materials and references

Courses and pedagogical approaches

- ☑ Fabricademy course: Open source Hardware - from fibers to fabrics[21]

Projects and Machines

- ☑ Kniterate[22]
- ☑ Studio Hilo[23]
- ☑ Little Wool Factory project[24]
- ☑ DIY braiding machines[25]
- ☑ Indira Loom[26]

Open Source Platforms

- ☑ Open Hardware Observatory[27]
- ☑ Open Know-How [28]
- ☑ Appropedia[29]
- ☑ Low-tech lab[30]
- ☑ Fab Labs.io[31]

[21] http://fabricademy.fabcloud.io/handbook/classes/07_open_source_hardware/
[22] https://www.kniterate.com/product/kniterate-the-digital-knitting-machine/
[23] https://www.studiohilo.com/open-tools
[24] http://fabricademy.fabcloud.io/shemakes/handbook/2.-innovation-services/Lab-to-Lab-Research/
[25] https://www.youtube.com/watch?v=yV0ecqW1MSs&ab_channel=MrInnovative
[26] https://class.textile-academy.org/2022/nanditha-nair/assignments/week10/
[27] https://en.oho.wiki/wiki/Home
[28] https://search.openknowhow.org/
[29] https://www.appropedia.org/Welcome_to_Appropedia
[30] https://lowtechlab.org/en/tools/contribute
[31] https://projects.fablabs.io/

- ☑ Make.works[32]
- ☑ Ifixit[33]

Skills to develop:

- Engineering/Industrial designing
- Making
- Hacking
- Repairing
- Analyzing Systems and Impacts
- Sharing and documenting
- Animating Communities

6.5. Smart Wearables Technology

When we talk about wearable devices or innovative wearable technology, we are referring to electronic devices designed to be worn on the body or clothes. These textiles are intelligent systems that monitor or communicate ambient circumstances and detect/process the wearer's state (Júnior, H. L. O. et al., 2022).

They first appeared in the late 1980s in Japan and have become increasingly popular in recent years due to the advances made in science. The term smart textiles emerged in the late 1990s when intelligent materials were introduced into the textile industry and textile products. Smart textiles can be defined as textiles that can sense environmental stimuli, react to them, and adapt to them by integrating functionalities in the textile structure (Van Langenhove et al., 2007).

Smart textiles can be classified as follows:

- Active smart textiles, which respond to external conditions
- Passive smart textiles, textiles that sense external conditions
- Ultra-smart textiles, textiles that sense, react, and adapt themselves to conditions (Júnior, H. L. O. et al., 2022).

Passive smart textiles can only sense the environment, and they serve as sensors. Then, there are active smart textiles that can sense the stimuli from the environment and react to them. They have an additional function as an actuator. Furthermore, so-called very smart textiles can adapt their

[32] https://make.works/

[33] https://www.ifixit.com/

behavior to dynamic conditions. In order for a textile structure to be called a smart textile, both sensor and actuator components need to be present in the material, which a processing unit can, in turn, supplement to steer the exchange between both components.

As smart textiles promise support in almost all situations, including applications in sports, health, home, living, mobility, or building, new markets and business models may be opened for both consumer and technical products (Priniotakis et al., 2022). Although smart textiles hold great promise for current and future applications in the domain of building and living, their application is often limited and hampered by a significant number of smaller and larger factors: (1) certification and standardization of new products, (2) sustainability and circularity, and (3) functionalization (interactivity).

The document "Smart Fabric Textiles: Recent Advances and Challenges" included in the Transitions mapping presents the primary type of Smart Fabric Textiles.

- Smart-color-changing fabric textiles
- Temperature-Controlling Fabric Textiles
- Shape Memory Fabric Textiles
- Waterproof and Breathable Fabric Textiles
- Wearable Electronics Smart Textile
- Phase-Changing Textiles

Smart textiles have a broad spectrum of applications ranging from daily usage to high-tech usage. We would consider textiles used for the following broad categories:

- Comfort wear
- Heat protection
- Medical applications
- Military applications
- Computing textiles
- Fashion
- Aviation
- Space research

6.6. Towards greater sustainability in production processes

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As in many other areas of the textile industry, sustainability and circularity are priorities in dyeing and finishing machinery innovations. The EU REACh Regulation (EC Regulation 1906/2007, Registration, Evaluation and Authorisation of Chemicals) has certainly given an initial impetus to the search for alternatives based on the use of hazardous or polluting substances. Thanks also to this regulation, in recent years, we have witnessed the development of alternative and environmentally sustainable materials and technologies focused on reducing energy, chemicals, and water use.
The following examples are some of the technologies developed by European companies aiming to develop more environmentally friendly technologies that promote circularity in the industry.

6.6.1. Dyeing processes

The increasingly damaging impact of the textile process on the environment has led to the progressive development of dyeing processes based on the use of natural dyes, which practically disappeared from industrial textile production in the last century. In the following paragraphs, we will present some of the most recent innovations in this field at the European level.

DyeCoo - CO2 Dyeing
The Dutch company DyeCoo has developed the world's first 100% water- and process-chemical-free textile processing solution. DyeCoo uses patented and industrial-proven technology based on CO_2 without water. The technology uses reclaimed CO_2 as the dyeing medium in a closed-loop process. When pressurized, CO_2 becomes supercritical (SC-CO_2). In this state, CO_2 has a very high solvent power, allowing the dye to dissolve quickly. Thanks to the high permeability, the dyes are transported quickly and deeply into fibers, creating vibrant colors. Contrary to traditional processing, there is no waste production in this process, as it generates no waste products and wastewater to be purified.
This technology is energy efficient since no water needs to be evaporated, and it has efficient color absorption and short processing cycles. These characteristics also help to reduce operating costs significantly.
In addition, dyeing without water opens up new opportunities for the textile industry, allowing fabrics to be dyed anywhere independent of the availability of clean water. Such opportunities would allow production closer to the market and with shorter delivery times.

Alchemie Technology - Endeavour Waterless Smart Dyeing process
Alchemie Technology Ltd. is an England-based company that has recently developed the Endeavour Waterless Smart Dyeing process, a digital, on-demand textile dyeing process for polyester fabrics. The Endeavour system reduces wastewater by more than 95%, offering significant savings in energy consumption, materials, and labour costs compared to traditional dyeing processes (Textile World, 2020).

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COLOURizd – QuantumCOLOUR for yarn

COLOURizd developed QuantumCOLOUR, an innovative, sustainable commercial technology for colouring cellulosic and synthetic yarns. This technology permits Zero Wastewater Discharge and a reduction in Water Consumption equal to 98%. Furthermore, it permits the reduction in carbon footprint (73%) and in energy consumption (50%).

Thanks to the low water and power requirements, the technology developed by COLOURizd makes it an ideal choice for locations with limited resources or stringent environmental laws.

6.6.2. Finishing processes

Plasma technology

Plasma treatment is a surface modification process in which a gas (air, oxygen, nitrogen, argon, carbon dioxide, etc.) is ionized due to two electrodes, between which an electric field is created at a high frequency. Plasma technology is one of the environmentally friendly production technologies as it does not use solvents and does not generate by-products that require appropriate disposal. This technology succeeds in eliminating or reducing solvents in textile processing; at the same time, it is more effective than the chemicals otherwise used for finishing activities. Depending on how it is activated and the working power, it can generate low or very high temperatures and is referred to as cold or hot plasma, respectively. The possibility of activating plasma at non-degrading temperatures, using either ambient or low pressure, makes it suitable for numerous technological applications, mainly related to surface coatings and industrial processing.

Sol-gel deposition

Among the various innovative approaches that can be used to functionalize textiles through nanostructured coatings, strong scientific and industrial interest is directed towards sol-gel technologies. Such technology enables organic-inorganic hybrid coatings on textile substrates with chemical-physical properties that can be modulated according to the desired objectives.
The sols of organic molecules allow the formation of hybrid materials that can offer almost unlimited potentialities for applying functional coatings to textiles, a field of increasing scientific and applicative interest in recent years, also thanks to their technical uses.

Ink-jet printing

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In recent years, ink-jet printing technology has found its natural application in industrial production cycles, thanks to its versatility and the quality of its performances, allowing the production of significant volumes capable of containing energy consumption and using dyes. The principle of digital printing is based on the deposition of microscopic ink droplets on the surface of textile substrates in order to reproduce the design desired design. Ink-jet printing is, for the near future, the unique application system for both printing and textile finishing: many finishing treatments can be provided by more advanced ink-jet technologies.

6.7. Recyling technologies

6.7.1. Main recycling technologies

Recycling is considered one of the leading solutions to tackle the textile waste problem. Such technology is significant as EU legislation will soon propose a minimum recycled content for all products designed and manufactured by EU companies under the Ecodesign for Sustainable Products Regulation.
Textile waste from the fashion industry can be categorized into industrial waste, pre-consumer waste, and post-consumer waste (Wang, 2006). As shown in the figure number 15 below, these waste categories have different difficulty levels of recyclability (Eppinger, 2022).

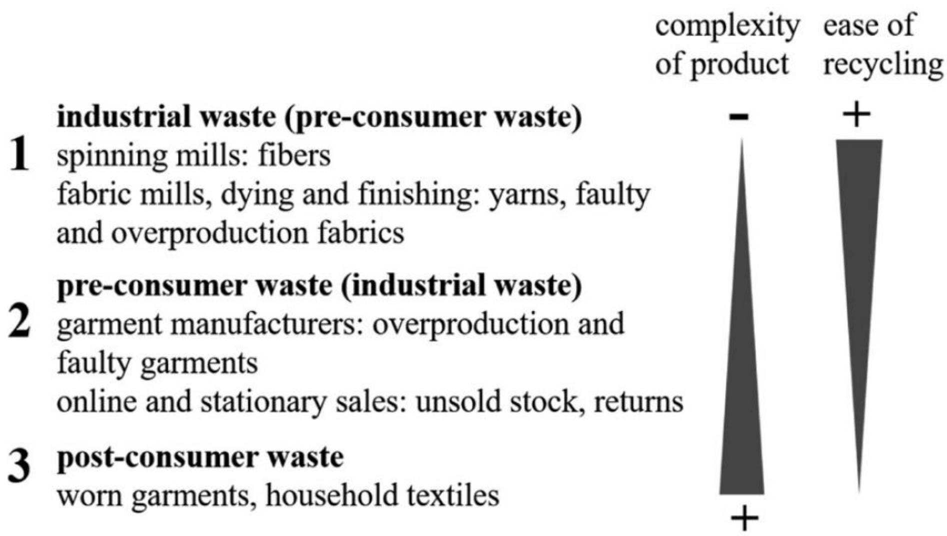

Figure 15. Waste categories in the fashion industry and ease of recyclability. Source: Eppinger, E. (2022).

According to the analysis conducted by McKinsey & Company, we are witnessing the emergence of innovations in the European textile recycling landscape.
We will briefly present the recycling technologies in today's landscape, considering some fiber types, as recycling technologies mostly apply to specific fibers or fiber blends. The leading recycling technologies are:

- **Mechanical recycling**

Mechanical recycling is an established technology in the market (TRL 9) with decades of experience. This technology can be used to recycle different types of fibers, from wool or other natural cellulose-based fibers and synthetic fibers (polyester, polyamide, viscose, acryl, PP). Every type of textile waste, material type, and textile product can be processed via mechanical recycling. However, the required machinery and the potential output are chosen considering the type of fiber in combination with the textile structure. Wool recycling is particularly developed in Prato, Italy, where there is a long recycling tradition (Duhoux, T. et al., 2021). The quality of the input plays a crucial role in obtaining a higher quality of fiber output.

Recycled cotton, after wool, has the highest value compared to virgin fibers. Cotton has been recycled for a long time and can be used in both mechanical shredding, such as Circular System's Texloop fiber, and chemical processes, whereby it is broken down to its cellulosic structure and converted to a viscose/lyocell fiber, such as Renewcell's Circulose. (Textile Exchange, 2022d).

One of the mechanical advantages is that every type of textile waste, material type, and type of textile product can be processed via mechanical recycling. Therefore, recycling mechanically can be the solution for those textiles that can not be recycled through chemical or thermo-mechanical technologies.

However, mechanical recycling technologies can present two problems regarding the REACH Regulation. The first one concerns the chemical substances contained in the products produced years ago, which are not more compliant with the regulations of today and that can be unintentionally incorporated during recycling. The second one concerns the textiles that can be contaminated with the chemical substance during use, and that can't be washed out with a conventional cleansing process (Duhoux, T., et all, 2021).

One of the advantages of mechanical recycling is that every type of textile waste, material type, and types of textile product can be processed via mechanical recycling. Hence, those textiles that can not be recycled through chemical or thermo-mechanical technologies can be recycled mechanically. Furthermore, the process uses a relatively low number of resources.

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In addition, mechanical recycling is the only way to present natural fiber, like cotton fibers, maintaining the original properties even though they may be altered depending on the state of the fiber.

On the other hand, mechanical recycling processes present some disadvantages, like the output quality, resulting in fibers with lower quality compared to virgin fibers or non-fibrous material that need further processing to be used in textile production.
Furthermore mechanical recycling technologies can have two concerns regarding the REACH Regulation. The first one concerns the chemical substances contained in the products produced years ago, which are not more compliant with today's regulations and can be unintentionally incorporated during recycling. The second one concerns the textiles that can be contaminated with chemical substances during use and that cannot be washed out with a conventional cleansing process.
In thermal recycling, a distinction is made between thermo-mechanical recycling and thermo-chemical recycling.

Thermo-mechanical recycling
Thermo-mechanical recycling is a technology for recycling thermoplastic textiles (i.e. polyester, polyamide, polypropylene) by melt-processing them into granulate and new fibers. It is also a cost-effective, efficient, and well-known process, which means it can be easily implemented (Duhoux, T. et al., 2021).

Thermo-chemical recycling
Thermo-chemical recycling is a process using a partial oxidation reaction of polymers to produce low molar mass components or heat to degrade polymers to monomers that can be used as feedstock for the chemical industry, with the exclusion of fuels used for energy production or other combustion or energy recovery processes. It is considered a mature technology, although developments to allow the production of raw materials for the chemical industry (as opposed to energy recovery or fuel production) are very recent. Up to now, not many waste gasification processes have been piloted and tested, but there are a few that have already been implemented as industrial plants (TRL 9) processing actual waste.

Chemical recycling
The chemical recycling is applicable for:
• Closed-loop or open-loop system for pure polyester (PET) and Nylon 6 materials;
• Open-loop system for cotton materials.

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Chemical recycling by depolymerisation is one way to recycle synthetic fibers: the recycling of polyester polyethene terephthalate (PET) and nylon six now occurs on a commercial, albeit limited, scale.
Regarding cellulosic fibers, as cotton, they can be chemically recycled by a pulping process followed by solution spinning to produce regenerated cellulosic fibers (Roos, S., et al. I, 2019). Cotton and other cellulose-based fibers are often recycled through (bio)chemical recycling (Deckers, J., et al., 2023)
All these textile recycling technologies depend on the quality input: it determines the efficiency and the economic viability of the recycling process. Therefore, once again, the importance of introducing products on the market that are designed to be optimally recycled emerges.

6.7.2. Current and future recycling capacity

Based on information released by EU Science Hub – Joint Research Center during the Ecosystex Conference 2023, this section provides an overview of the current and future recycling capacity in Europe.

Current recycling capacity
- Dominated by mechanical & open-loop recycling (>12 plants with capacity > 5 Mt/yr)
- Total capacity for closed-loop recycling: 0.2 –0.3 Mt/yr (mostly post-industrial waste)

Future recycling capacity
- Most closed-loop recycling, more chemical recycling (~ 50 plants)
- Capacity increase, with claimed future capacity by industry of > 1.2 Mt/yr for closed loop recycling

Geographic distribution
- N/W/S Europe
- Abundant in Member States with strong textile industry

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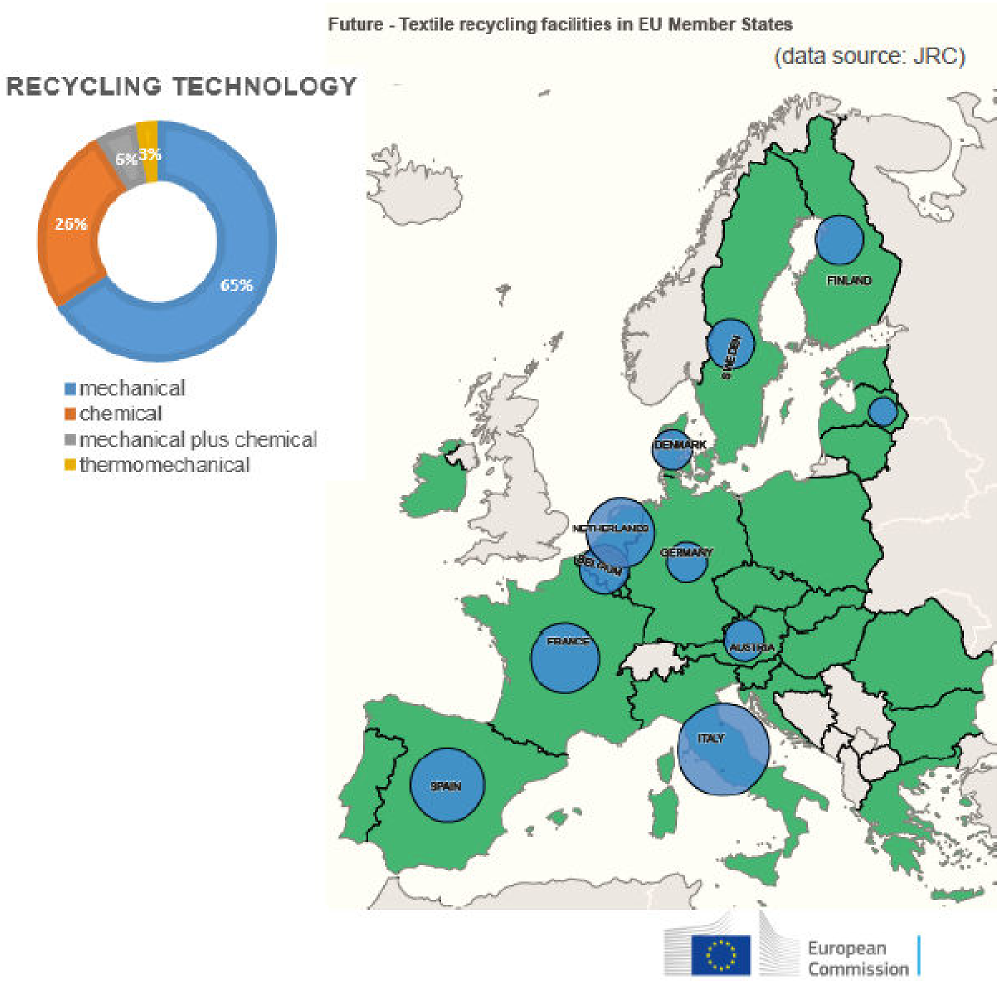

Figure 16. Future-Textile recycling facilities in EU Member States. Source: Joint Research Centre - European Commission

7. Feedback reporting

FEEDBACK SUMMARY TRANSITIONS PARTNERS ON DXXX			
FEEDBACK AREAS	**STRENGHTS**	**WEAKNESSES / IMPROVEMENT NEEDS**	**ACTION TAKEN**
Content / Writing	Complete, contemporary and rather consistent overview.	References could be grouped and in any case	

		referencing style should be consistent.	
Content / Writing		Referencing style should follow harvard in-text style	References updated according to Harvard Style
Content / Writing	The report offers a comprehensive mapping focusing on the latest textile innovations and contemporary references.	It is necessary to fix grammar and orthography mistakes	Document Proofreading

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